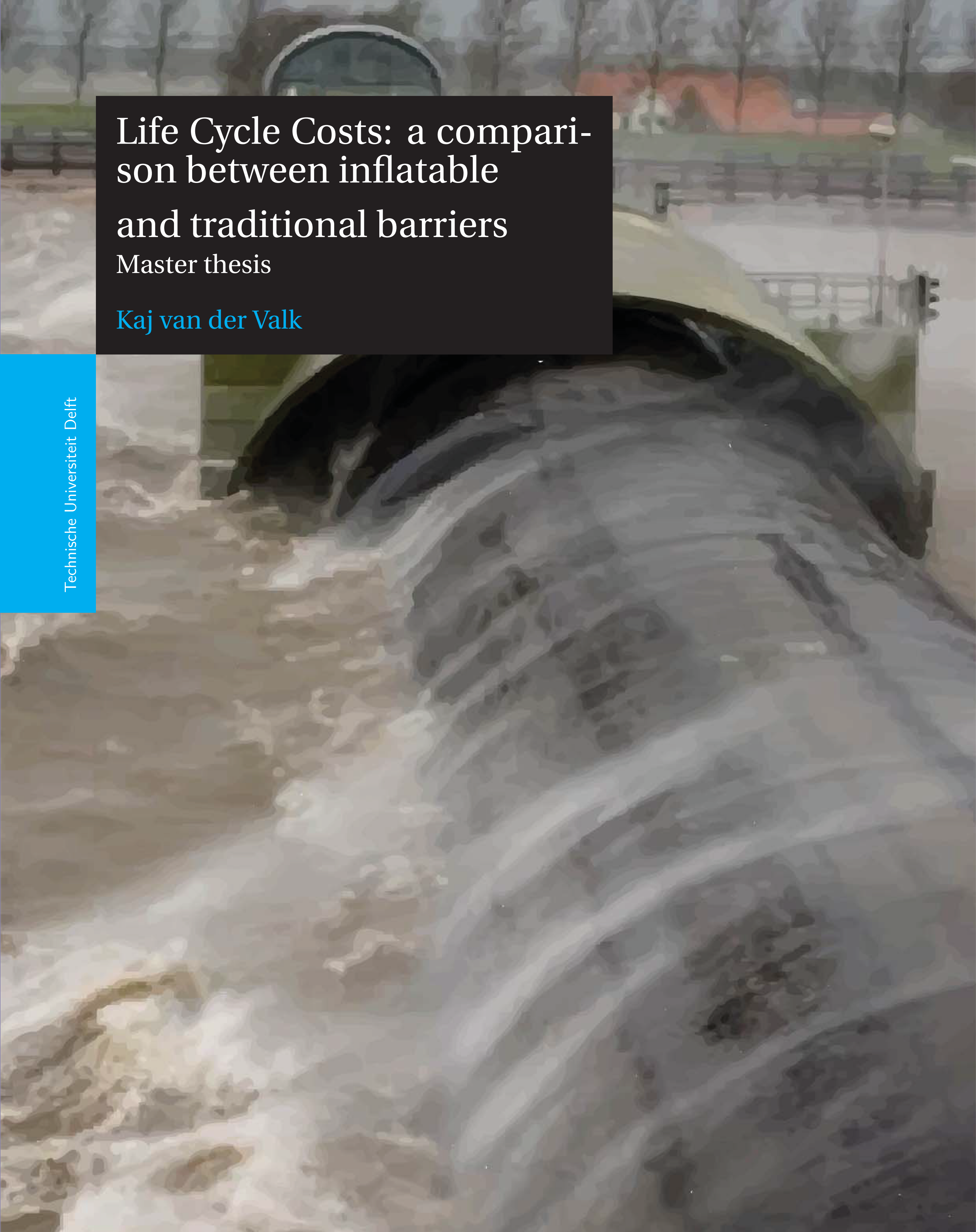

Life Cycle Costs: a comparison between inflatable and traditional barriers

Master thesis

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Technische Universiteit Delft

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bam

Challenge the future

Life Cycle Costs: a comparison between inflatable and traditional barriers

Master thesis

by

Kaj van der Valk

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The cover image is an edited photo, the original comes from Delta Marine Consultants (DMC) (2011).

Abstract

In December 2002 the highly innovative inflatable storm surge barrier near Kampen in the Netherlands was finished. This Ramspol barrier (named after the small villages next to it) has to protect the area surrounding the "Zwarte Meer" during north-western storms. These storms result in water setup that can cause severe problems for the very low area in the Eastern part of the Netherlands. According to Bouwdienst Rijkswaterstaat (2007), one of the reasons to build an inflatable barrier instead of a more traditional barrier, amongst others reasons, was that it was expected to be an economically preferable solution. No real proof for this claim exists until now. Van Breukelen (2013) concluded that an inflatable barrier in Galveston would be less costly than other barrier types, but her cost calculations were very basic. Dirkmaat (2011) concluded that an inflatable barrier in the Spui (in the Netherlands) would be four to twenty-five times as expensive as other options for this location. This thesis focusses on a Life Cycle Cost (LCC) comparison between inflatable barriers and 'traditional' vertical lifting gate barriers. This means that all costs that occur during the lifetime of the barriers are taken into account.

During this thesis a case study has been performed for the location of the Hartel barrier near Spijkenisse in the Netherlands. An inflatable barrier based on Ramspol has been designed for that location with the same requirements that hold for the original Hartel barrier. Based on this design the construction costs have been determined for such a barrier and these have been compared to the construction costs for the original barrier. Then maintenance strategies based on decompositions for both types of barriers have been determined in order to predict and calculate the expected maintenance costs in a deterministic way. The influences of the discount rate and the lifetime of the membrane of inflatable barriers are also addressed. In order to increase the reliability and get an insight in sensitivities a sensitivity analysis has been performed by making use of a Monte Carlo simulation. This provides results with a 5%, 50% and 95% confidence level. The LCC costs for both barriers are compared and checked with the deterministic results. The results for the deterministic calculations are very similar to those from the sensitivity analysis.

Since this thesis is about a LCC comparison between the general types of barriers some general aspects, e.g. the influence of gate length, water depth, ship collision, etc., have been investigated. This is done mainly in a qualitative manner due to time considerations. The possible effects of the phenomena on both types of barriers are studied per phenomenon. These results are linked to the case study results and combined.

The most important conclusions that follow from this thesis are:

- For an inflatable barrier at the Hartel location both the construction- and the maintenance costs are lower compared to the original vertical lifting gate barrier. Over the total life cycle a cost reduction of 15% to 20% could be achieved (see table 1). The LCC with a 95% confidence level (upper bound) for the inflatable barrier is still about €8 million less lower than the LCC for the original barrier with a confidence level of 5% (lower bound).

Barrier	Construction	PV maintenance (mean)	Total PV (mean)	PV (5%)	PV (95%)
Hartel	€63.700.000	€36.600.000	€100.300.000	€95.700.000	€104.900.000
Inflatable Hartel	€58.400.000	€24.700.000	€83.100.000	€78.700.000	€87.500.000

Table 1: Present Value for construction costs, maintenance costs and the total LCC and the 5% and 95% confidence levels (2014 price level)

- In general can be said that inflatable barriers appear to be economically (and structurally) preferable when barriers are required with increased gate lengths or in deeper water. Furthermore, the design of inflatable barriers can possibly be improved by leaving out the abutments or by making it adaptable for increased water levels. This options increase the number of applications for inflatable barriers.

- Based on the findings of this thesis the scores for inflatable barriers in a comparison between storm surge barriers is updated. Based on this updated comparison can be said that inflatable barriers should be considered as a serious option for almost all circumstances (see table 2).

	Mitre gate	Vertical lifting	Flap	Horizontal rotating	Vertical rotating	Inflatable
Span > 30m	-	+	+	+	+	+
Span > 100 m	-	-	+	+	-	+
Water depth > 10 m	+	+	+	+	+	+
Impact upon landscape	+	-	+	+	-/+	+
Maintenance	+	+	-	0	+	+
Currents and waves	-	+	0	0/+	0/+	0
Closure time	+	+	+	+	+	+
Space required	+	+	+	-	+	+
Colliding ships	0/-	+	+	0/-	+	0
Reliability	-/+	+	0/+	-/+	+	0
Clearance height	+	-	+	+	-/+	+

Table 2: Updated version of table 3.1: - Not favorable up to not feasible, 0/- Below average/vulnerable, 0 Average/possible, 0/+ Above average, + Favorable/proven technology, -/+ Score depends on design choices and conditions (updated version of (Dircke, Jongeling, & Jansen, 2012, Table 11))

Critical aspects for the LCC of the barriers appear to be the lifetime of the membrane, the conservation costs for the doors and the maintenance on the CS for the Hartel location. These parts are responsible for about 80% of the maintenance costs. The membrane contributes relatively the most to the spread of the results and should be one of the focus points in future research.

The most important recommendations that follow from this thesis are:

- Create a database with construction and maintenance costs for storm surge barriers. This is expected to be very beneficial for LCC comparison purposes and probably decision- and policy making purposes in general.
- Create a 3-D FEM in order to increase the reliability of the calculations and check the effects of for instance the length of a gate.
- Investigate the possibilities for inflatable barriers without abutments. This is expected to solve some issues of the current design (stress concentrations and folds) and is expected to be less costly.

Preface

This report is submitted in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering at Delft University of Technology. This thesis has been made solely by me, however large parts of the text are based on previous research. I tried my best to provide all the references to my sources.

This research investigates and compares the Life Cycle Costs for inflatable- and traditional barriers. Literature predominantly claims that inflatable barriers are less costly, but no real proof for this claim exists. A case study is performed at the location of the Hartel storm surge barrier near Spijkenisse in the Netherlands. An inflatable barrier, based on the Ramspol barrier near Kampen in the Netherlands, is designed for the same requirements as the original Hartel barrier in order to compare their Life Cycle Costs. General conclusions are based on this case study.

Since I prefer to work on the big picture in stead of focussing on the details, working on this report was very satisfactory for me. It forced me to study subjects that are only touched during the normal curriculum, like life cycle costs and maintenance regimes, which I believe makes me a more complete engineer.

I would like to thank my graduation committee for their input and referrals, this gave me the opportunity to meet with experts on these subjects and increase the reliability of my work. Next to this I would like to thank BAM and especially the coastal department of BAM Infraconsult for the opportunity to do my thesis as an intern and to be part of their team. Furthermore, I would like to thank the experts I met and who provided insights and data, without them the results would not have been as good.

Lastly, I would like to use this opportunity to thank everyone who supported me during the writing of this thesis and during my study in general.

Kaj van der Valk
the Hague, 17 November 2014

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Glossary

Asset	Whole building or structure, system or a component or part (ISO, 2008).
Capital Budgeting	Capital budgeting is a process used by companies for evaluating and ranking potential expenditures or investments that are significant in amount. It usually involves the calculation of each project's future accounting profit by period, the cash flow by period, the present value of the cash flows after considering the time value of money, the number of years it takes for a project's cash flow to pay back the initial cash investment, an assessment of risk, and other factors(Averkamp, -).
Deflation	Sustained decrease in the general price level (ISO, 2008).
Discount Rate	Factor or rate reflecting the time value of money that is used to convert cash flows occurring at different times to a common time (ISO, 2008).
Discounting Cost	Resulting cost when the real cost is discounted by the real discount rate or when the nominal cost is discounted by the nominal discount rate (ISO, 2008).
Disposal Cost	Costs associated with disposal of the asset at the end of its life cycle, including taking into account of any asset transfer obligations (ISO, 2008).
End-of-life Cost	Net cost or fee for disposing of an asset at the end of its service life or interest period, including cost resulting from decommissioning, deconstruction and demolition of a building; recycling, making environmentally safe and recovery and disposal of components and materials and transport and regulatory costs (ISO, 2008).
Equivalent Annual Costs	The annual cost of owning an asset over its entire life. Equivalent annual cost (EAC) is often used by firms for capital budgeting decisions. (Investopedia, -).
Hydraulic head	The force exerted by a column of water expressed by the height of the liquid above the point at which the pressure is measured. As the force of a water mass is directly proportional to the (hydraulic) head, it is often used to express pressure on hydraulic structures (de Vries, 2014).
Inflatable barrier	An inflatable dam with the function of storm surge barrier
Inflation	Sustained increase in the general price level (ISO, 2008).
Life Cycle	Consecutive and interlinked stages of the object under consideration (ISO, 2008).
Life Cycle Assessment	Method of measuring and evaluating the environmental impacts associated with a product, system or activity, by describing and assessing the energy and materials used and released to the environment over the life cycle (ISO, 2008).
Life Cycle Cost	Cost of an asset or its parts throughout its life cycle, while fulfilling the performance requirements (ISO, 2008).
Life Cycle Costing	Methodology for systematic economic evaluation of life-cycle costs over a period of analysis, as defined in the agreed scope (ISO, 2008).

Maintenance Cost	Total of necessarily incurred labour, material and other related costs incurred to retain a building or its parts in a state in which it can perform its required functions (ISO, 2008).
Membrane	In this case: the reinforced rubber sheet that is used to create an inflatable barrier. See section 3.2.4 for more information.
NAP	Normaal Amsterdams Peil: Amsterdam Ordnance Datum. The vertical reference point in use for large parts ofWestern Europe which was originally established in 1684 for use in the Netherlands (de Vries, 2014).
Net Present Cost	Sum of the discounted future costs (ISO, 2008).
Net Present Value	Sum of the discounted future cash flows (ISO, 2008).
Operation Cost	Costs incurred in running and managing the facility or built environment, including administration support services (ISO, 2008).
Period of Analysis	Period of time over which life-cycle costs or whole-life costs are analysed (ISO, 2008).
Present Value	Estimated current value of a future amount to be received or paid out, discounted (see discounting) at an appropriate rate, usually at the cost of capital rate (the current market interest rate). PV provides a common basis for comparing investment alternatives (BusinessDictionary.com, n.d.).
Present-Day Value	Monies accruing in the future which have been discounted to account for the fact that they are worth less at the time of calculation (ISO, 2008).
Real Discount Rate	Factor or rate used to relate present and future money values in comparable terms, not taking into account general or specific inflation in the cost of a particular asset under consideration (ISO, 2008).
Residual Value	Value assigned to an asset at the end of the period of analysis (ISO, 2008).
Risk	Likelihood of the occurrence of an event or failure and the consequences or impact of that event or failure (ISO, 2008).
Sensitivity Analysis	Test of the outcome of an analysis by altering one or more parameters from initial value(s) (ISO, 2008).
Storm Surge Barrier	A storm surge barrier is a partly moveable barrier in an estuary or river branch which can be closed temporarily. See section 3.1 for the full definition as it is presented by De Vries (2014).
Time Value of Money	Measurement of the difference between future monies and the present-day value of monies (ISO, 2008).
Weir	A low wall or dam built across a stream or river to raise the level of the water or to change the direction of its flow
Whole Life Cost	All significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements (ISO, 2008).
Whole Life Costing	Methodology for systematic economic consideration of all whole-life costs and benefits over a period of analysis, as defined in the agreed scope (ISO, 2008).

Acronyms

2-D	Two Dimensional
CDF	Cumulative Distribution Function
CS	Control System (the ICT)
EAC	Equivalent Annual Cost
EPDM	Ethylene Propylene Diene Monomer
FEM	Finite Element Method
FRP	Fibre Reinforced Plastics
ICP	Intra Carcass Pressurization
ICT	Information and Communications Technology
IHNC	Inner Harbor Navigation Canal
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCC	Life Cycle Costing
MC	Monte Carlo
NAP	Normaal Amsterdams Peil
NPC	Net Present Cost
NPV	Net Present Value
OS	Operating System (mechanical parts)
PA6	Polyamide 6
PV	Present Value
R	Resistance
S	Strength
SCF	Stress Concentration Factor
SLR	Sea Level Rise
ULS	Ultimate Limit State
USA	United States of America
UV	Ultra Violet
WLC	Whole Life Costing
WLC	Whole Life Cost

List of Symbols

α	[rad]	Angle
d	[%]	Real discount rate
B	[m]	Width
β_1	[-]	Skewness
β_2	[-]	Kurtosis
C	[€]	Costs
d	[m]	Depth
F	[kN]	Force
g	[m/s^2]	Gravitational acceleration
γ	[-]	Safety factor
H	[m]	Height
h	[m]	Water level
I	[-]	Inflation rate
k	[-]	Wave number
ξ	[-]	Multiplication factor
L	[m]	Length
μ	[-]	Mean
n	[years]	Number of years
N	[%]	Nominal discount rate
n	[-]	number of draws
p	[kN/m^2]	Pressure
p	[years]	Period of analysis
P	[%]	Probability
ϕ	[rad]	Angle
π	[-]	The ratio of a circle's circumference to its diameter.
q	[-]	Discount factor
R	[kN]	Strength
r	[-]	Reflection rate
R	[%]	Discount rate
RH	[kN]	Resulting horizontal force
ρ	[kg/m^3]	Density
RV	[kN]	Resulting vertical force
σ	[-]	Standard deviation
T	[kN]	Tensile force in the membrane
T	[s]	Wave period
V	[-]	Coefficient of variation
y	[m]	Vertical location
z	[NAP+m]	Vertical location

1 Introduction

At the end of 2002 the innovative inflatable barrier near Ramspol in the Netherlands was finished. It is the first inflatable dam that is built to work as a storm surge barrier. During high waters at the IJsselmeer the barrier is inflated to protect the areas surrounding the Zwarte Meer. Under normal conditions the membrane is stored under water and ships may pass. The barrier consists of three identical bellows, each with a maximum length of about 80 meters. Figure 1.1 shows a bellow that is almost completely inflated. The last time the barrier has been tested by a storm was in December 2012, when a storm from the north west caused significant wind setup. The barrier is inflated every year before the storm season begins to test it.

Figure 1.1: Photograph of an upcoming bellow of the Ramspol barrier (Bouwdienst Rijkswaterstaat, 2007)

Currently, the inflatable barrier near Ens and Kampen is the only inflatable storm surge barrier in the world. Although it is thought that this structure has more advantages than disadvantages, it has not been built at any other location. Amongst these advantages are the fact that it can close large openings without intermediate abutments, when inactive the barrier is stored under water which is aesthetically preferable and it is expected that maintenance can be done easily (Jongeling, 2005). It is also expected to be an economically preferable solution compared to traditional barriers (Bouwdienst Rijkswaterstaat, 2007). However, proof for this claim is not yet available. The expectation is shared by Van Breukelen (2013), who calculated that an inflatable barrier for the Galveston Bay in Texas would be about 4 times less costly than other barrier types. It must be noted that her cost calculations were very basic. Dirkmaat (2011) concluded on the other hand that an inflatable barrier in the Spui in the Netherlands would be 4 to 25 times more expensive than other options. In this case one of the main reasons to construct a barrier was to prevent salt intrusion. This thesis is the first report especially written to address the costs for the highly innovative inflatable barrier compared to traditional barriers.

A very good method to evaluate and compare all relevant costs that occur during the lifetime of an asset is Life Cycle Costing (LCC). It is a very useful tool to provide input for a decision making or an evaluation process. One of the decision making purposes for which an LCC can be used is: *"Choices between alternative designs for the whole or part of a constructed asset during the design and construction stage"* (ISO, 2008). In this thesis whole constructed assets will be discussed.

The goal for this thesis is to provide an LCC comparison for both an inflatable- and a 'traditional' barrier, which can be used as input for decision making purposes in the future. First a case study will be performed in which an inflatable barrier will be designed at a location of a vertical lifting door barrier. In this way barriers with the exact same requirements can be compared. In the end more general conclusions will be drawn based on this case study results.

1.1. RESEARCH QUESTIONS

This section will discuss the research questions for this thesis.

1.1.1. RESEARCH QUESTIONS

Answering the research questions is the ultimate goal of the thesis. All steps taken during this thesis will have the purpose of partly answering the questions.

MAIN RESEARCH QUESTION

Taking Life Cycle Costs into account, might an inflatable barrier be economically preferable to a 'traditional' vertical lifting gate barrier?

SUB RESEARCH QUESTIONS

1. *What are the governing factors that influence the LCC for both types of barriers?*
2. *Would an inflatable barrier have been an economically preferable alternative to the Hartel barrier when taking LCC into account?*
3. *Generally speaking, what can be said about the LCC comparison between inflatable barriers and vertical lifting gate barriers?*
4. *What is the effect on LCC of the inflatable barrier for varying lifetimes of the membrane?*
5. *What is the influence of the discount rate on the LCC comparison?*
6. *What maintenance regime is ideal for inflatable barriers?*
7. *What are the most uncertain factors and what can be done to improve their uncertainties?*

1.2. RESEARCH METHODS

The methods used to answer the research questions will be presented in this section.

1.2.1. CASE STUDY

In order to make a proper comparison it has been chosen to make use of a case study. Within this case study the LCC for an already existing vertical lifting gate barrier will be compared with the expected LCC for an inflatable barrier designed at the same location and for the same requirements. Performing a case study is very useful to determine first results and provide reference material.

1.2.2. DESIGN AT SUB SYSTEM LEVEL
In order to make a good estimation of the construction costs of the inflatable Hartel barrier, this barrier had to be designed at subsystem level. This means that for the larger parts of the barrier has been determined what size they should have.

1.2.3. DECOMPOSITION
To determine the maintenance costs for both barriers a decomposition is performed for both of them. This is a very useful method since it is much easier to determine a maintenance strategy and the maintenance costs for a part of the asset than for the complete asset in one time. Furthermore, it is more realistic since different parts will have their own regime. This decomposition is performed at the same level of detail as has been used for designing and determining the construction costs for the inflatable Hartel barrier.

1.2.4. MONTE CARLO SIMULATION
For the sensitivity analysis a Monte Carlo Simulation is programmed in Matlab. This simulation makes it possible to give confidence levels for the LCC. It is for instance possible to give the cost level of which it is 95% certain that the actual costs are lower. This way of simulating is also suggested by ISO (2008).

1.3. REPORT STRUCTURE
The report structure will be explained here. See figure 1.2 for the structure visualised.

Chapter 2 will start with an introduction about Life Cycle Costing, important aspects and usages. Furthermore the discount rate and costs groups that are in- or excluded are discussed.

In chapter 3 inflatables dams are discussed. The chapter will start off with an overview of barrier types and a score table to show (dis)advantages per type. Then general aspects of inflatable dams are handled and reference case Ramspol is introduced. Lastly possible locations for a case study are presented.

Chapter 4 will elaborate on the design of the membrane of an inflatable barrier and gives the results for the forces in the membrane for the two possible case study locations; the Hartel barrier and the Hollandse IJssel barrier. In the end the choice for the Hartel location as case study is discussed and the final shape of the membrane will be described.

Within chapter 5 the other design aspects, such as groundwork, foundation and abutments, are explained. This is a first step to determine the construction costs for an inflatable barrier in the Hartel Canal.

The actual construction costs are calculated in chapter 6. The construction costs for the inflatable Hartel barrier are based on the construction costs for Ramspol. They are mostly scaled versions of the Ramspol costs. Also the construction costs for the original Hartel barrier are presented. These costs will serve as input for chapter 8.

Another important aspect for LCC are the maintenance costs. These costs and maintenance regimes in general are discussed in chapter 7. Based on a decomposition of the barriers the maintenance costs are determined as accurately as possible. These will serve as input for chapter 8. Within this chapter also the influence of the lifetime of the membrane and the discount rate on the LCC are presented. Finally the deterministic values of the LCC for Ramspol-, inflatable Hartel- and the original Hartel barrier are presented.

Chapter 8 will present a sensitivity analysis for the LCC for both the inflatable- and the original Hartel barrier. Some of the input parameters will be given a distribution and a Monte Carlo Simulation is performed. In the end the statistical parameters for the LCC distribution are discussed.

In chapter 9 some other aspects are discussed since this thesis is about a LCC comparison between inflatable- and traditional barriers in general. The consequences for the LCC of for instance increasing the head, water levels and length of the barriers are discussed.

Finally chapter 10 will wrap up with the conclusions of this thesis and the recommendations for future research.

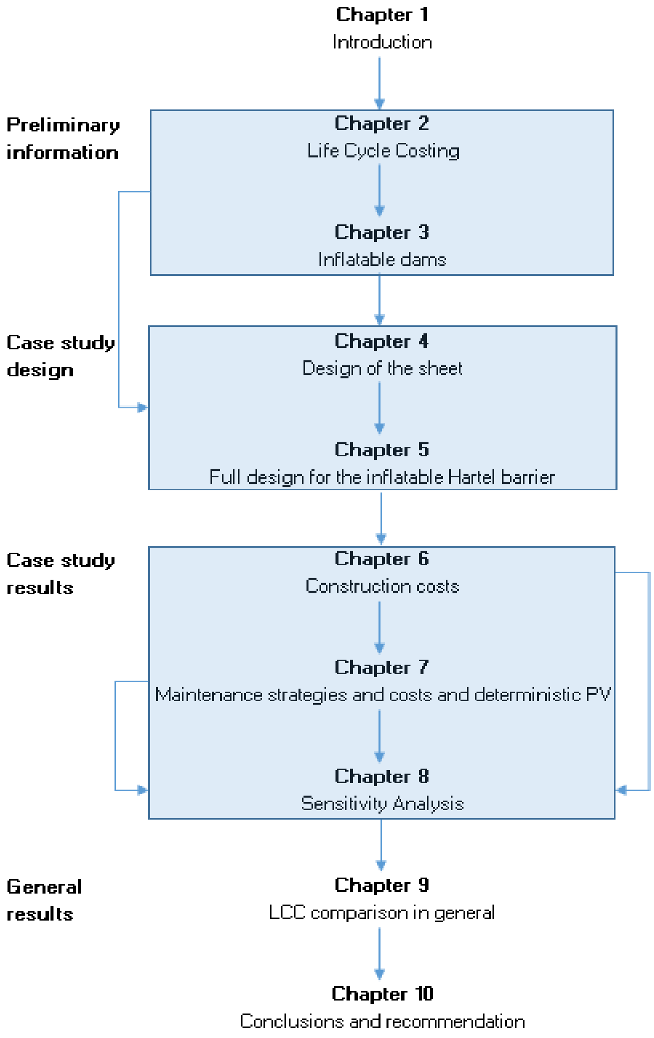

Figure 1.2: Report structure

1.3.1. DECIMAL SEPARATOR

For this thesis a comma (,) is used as a decimal separator and a dot (.) is used as a thousand (1000) separator.

1.3.2. LOOKING UP REFERENCES

If it is wished to use the same document or read the original information the source can be found in the References chapter in the end. All websites are clickable links and will direct you to the website or document requested.

2

LIFE CYCLE COSTING

Within this chapter the background of Life Cycle Costing (LCC) will be discussed. Section 2.1 will discuss the general ideas and purposes of LCC. The internationally standardized method to take Life Cycle Cost (LCC) into account (ISO 15686) will be treated in section 2.2. Finally, sections 2.3, 2.4 and 2.5 define the Net Present Value (NPV) and Present Value (PV) as it is used in this thesis, the discount rate and the costs that are taken into account during the lifetime of an asset.

2.1. GENERAL ASPECTS OF LIFE CYCLE COSTING

According to Woodward (1997) the concept of LCC was already introduced in the mid- to late 1970s. The goal is to optimise the value for money of assets by taking into account all cost factors during the operational life of the asset. By optimising the cost trade-offs the result will be a minimum life cycle cost of the asset. One of the very useful applications is decision making when several alternatives are considered. He claimed that many organisation did not take life cycle costs into account and are only interested in the initial purchase cost. A few exceptions are mentioned, namely military applications, buildings and public sector applications. A useful and short definition of LCC is presented by Harvey.

2.1.1. HARVEY'S LIFE CYCLE COSTING PROCEDURE

Figure 2.1 shows Harvey's definition schematically. According to Harvey LCC begins when the acquisition of an asset is first considered and ends at the end of its useful life. He distinguished four steps in his general procedure:

1. Define the cost elements of interest
2. Define the cost structure to be used
3. Establish the cost estimating relationships
4. Establish the method of LCC formulation

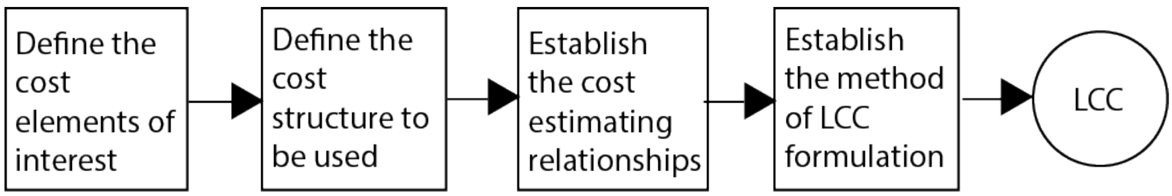

Figure 2.1: Harvey's life cycle costing procedure (Woodward, 1997)

Each of the steps will be discussed shortly.

THE COST ELEMENTS OF INTEREST

Within this step all cash flows, occurring during the functional life of the asset, should be defined. Although it is generally agreed that all costs should be taken into account, a precise identification was not available when Woodward discussed the issue.

DEFINING THE COST STRUCTURE

During phase 2 the costs should be grouped to be able to identify potential trade-offs in order to end op with an optimal LCC. The requirements to the cost structure are determined by the necessary depth and breadth. Figure 2.2 shows a four category structure used by Cost Analysis Improvement Group (1992). The structure should be such that it is optimal for LCC of the considered asset.

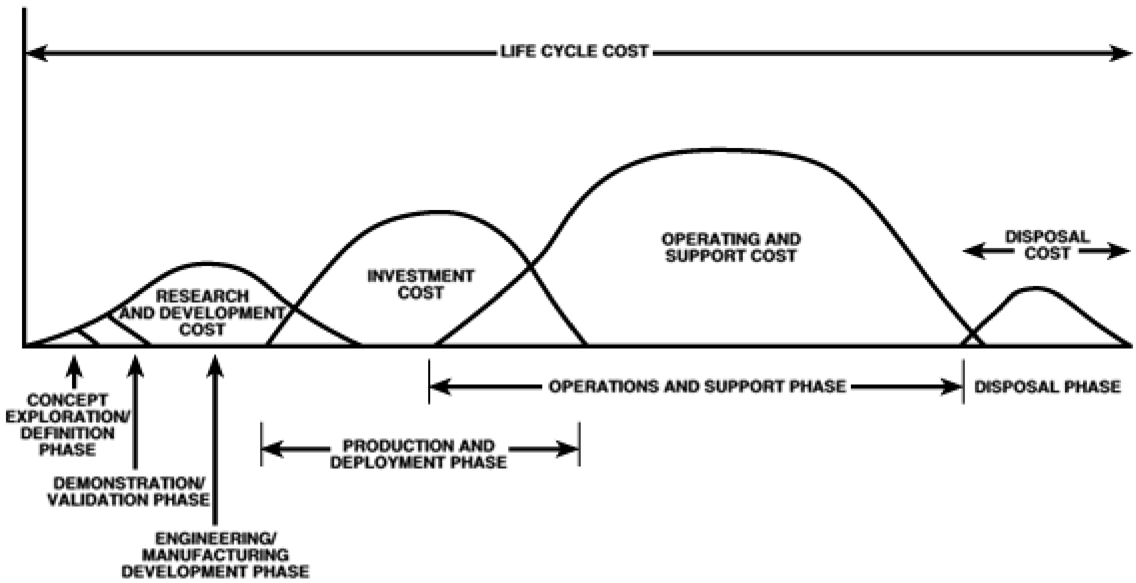

Figure 2.2: Example of cost categorisation (stages of life cycle costs) (Cost Analysis Improvement Group, 1992)

A COST ESTIMATING RELATIONSHIP

The goal is to get to a mathematical expression that describes the cost as a function of (an) independent variable(s). Usually historically-collected costs serve as basis for the estimations, very often utilising for example linear, parabolic or hyperbolic relationships.

ESTABLISHING THE METHOD OF LCC FORMULATION

In 1970 Kaufman proposed a new methodology to evaluate the asset's LCC. His method is based on an 8-step approach, shown in figure A.1 of appendix A. According to Woodward (1997) this is a method that "stood the test of time". Kaufman's eight steps are:

1. Establish the operating profile
2. Establish the utilisation factors
3. Identify all the cost elements
4. Determine the critical cost parameters
5. Calculate all costs at current prices
6. Ecalate current costs at assumed inflation rates
7. Discount al costs to the base period
8. Sum discounted costs to establish the net present value

2.1.2. COST TRADE-OFFS

By trading-off for example initial costs against operating costs an optimal investment can be found, see figure 2.3. From this figure can be seen that higher acquisition costs can result in lower operation costs. The optimal investment is determined by the minimum of the total cost (curve C). It can also be seen that low acquisition costs result in high maintenance costs ending up with a higher LCC. Furthermore, a small deviation of the minimum of curve C results only in a small increase in the total cost, giving the decision makers some flexibility.

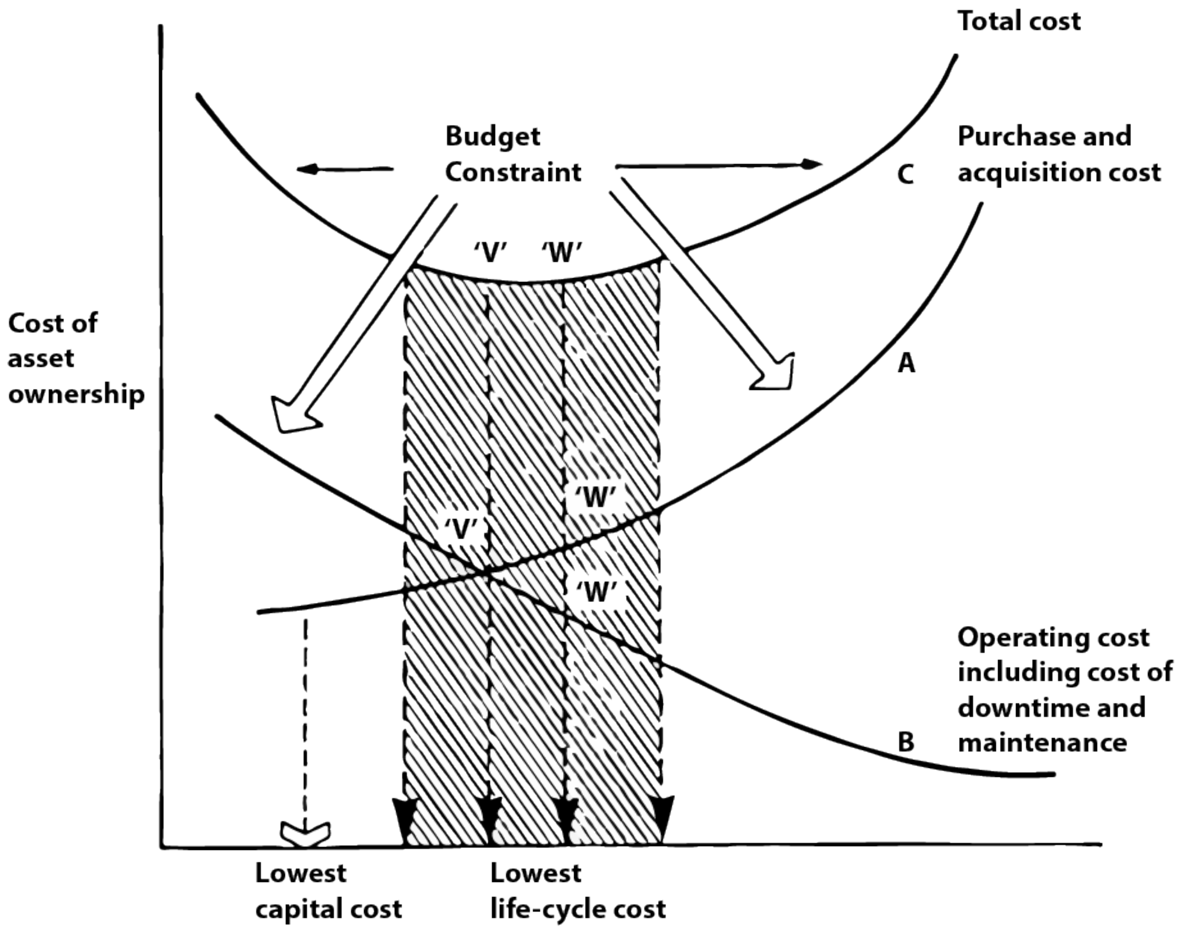

Figure 2.3: Cost trade-offs in asset ownership[1] (Woodward, 1997)

[1] With on the x-axis the technological state of the asset; for increased purchase and acquisition costs a more robust and advanced asset can be made and the costs for maintenance and downtime decrease

2.2. INTERNATIONAL STANDARD ISO 15686-5

Since 2008 an International Standard (ISO 15686-5), prepared by ISO (2008), is available for LCC for buildings and constructed assets. The goal is to provide a standardised method for LCC analyses for constructed assets, since there are many different definitions. One of the key objectives of this standard, and the most relevant one for this thesis, is:

"Help to improve decision making and evaluation processes at relevant stages of any project"

According to this standard quantified LCCs should be used as input for decision making or an evaluation process. However, also other analyses should be included in the decision making process, for example an environmental assessment, safety assessment, functionality assessment, etc. Important is to perform the LCC at the proper level of detail (see section 2.2.2).

2.2.1. LCC VERSUS WLC

A distinction has to be made between LCC and WLC. This is shown by figures 2.4 and 2.5. This thesis will focus on LCC. The typical scope of costs of both is shown by figure B.1 in appendix B.

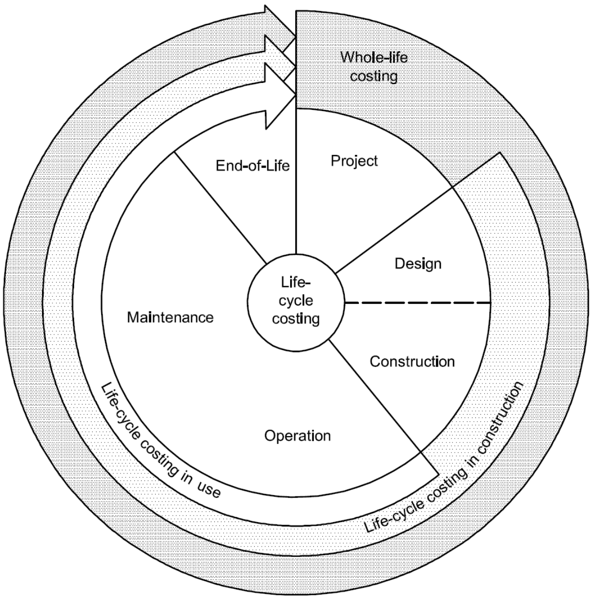

Figure 2.4: Schematic impression of LCC (ISO, 2008)

2.2.2. STRATEGIC LEVEL LCC - EVALUATION OF ALTERNATIVE STRATEGIC OPTIONS

An LCC analysis can be performed in three levels according to ISO (2008): at a strategic-, system- and detailed level. This is also shown in appendix C. This thesis will focus on the *strategic* level because "especially decisions placed in a strategic framework can create added value for the asset and help to identify the most cost-effective operations and maintenance regime", also shown in figure 2.6.

Within ISO 15686-5 some of many individual activities for LCCs at strategic level are given:

- Definition of the requirement for a constructed asset, in terms of functional and performance requirements
- Set design life and the level and period of analysis covered by the LCC analysis
- Client priorities
- Preliminary design concepts and related life cycle costing assumptions on specifications or service life plans

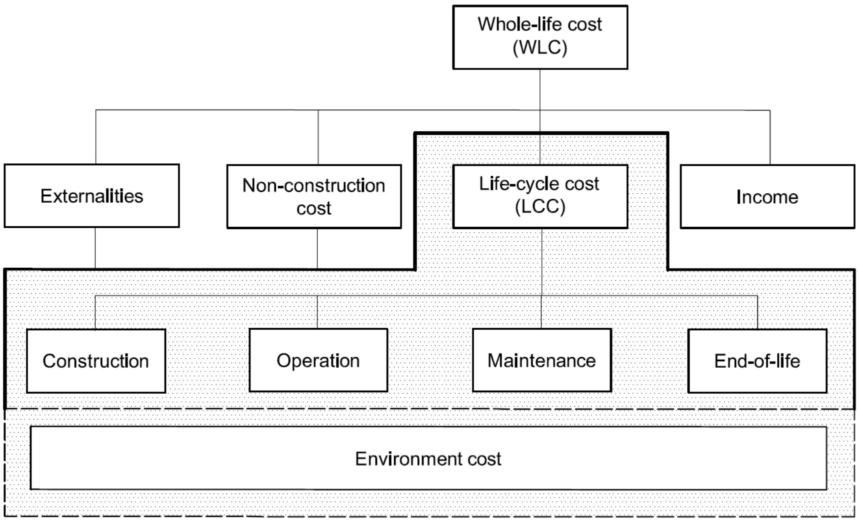

Figure 2.5: WLC and LCC elements (ISO, 2008)

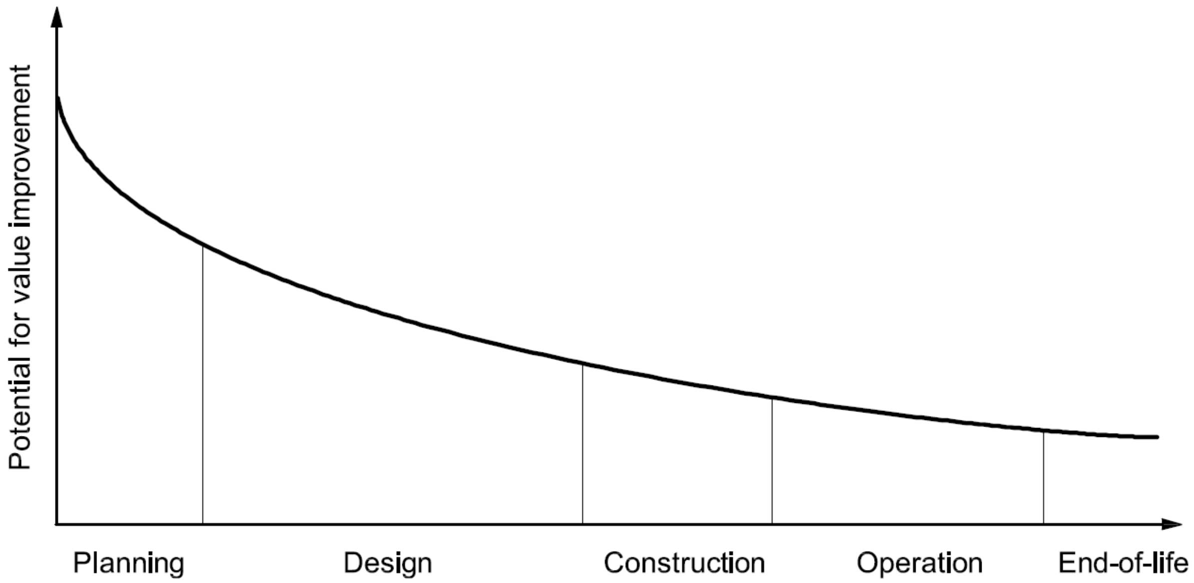

Figure 2.6: Scope to influence LCC savings over time (ISO, 2008)

- Acquisition route
- Purchase
- Cost of ownership considerations
- Other non-construction costs

It is allowed to make broad assumptions during this level. It is important to note all assumptions made.

2.3. NET PRESENT VALUE

The Net Present Value (NPV) can be used to compare alternatives over the same period of analysis. This is done by discounting future cash flows to the base date. It represents the present monetary sum that should be allocated for future expenditure of an asset. If only costs are taken into account the term Net Present Cost (NPC) may be used. This method is the normal measure used in an LCC analysis. The NPV should be calculated by using equation (2.1) (ISO, 2008).

$$X_{NPV} = \sum (C_n \cdot q) = \sum_{n=1}^{p} \left(\frac{C_n}{(1+d)^n} \right) \tag{2.1}$$

With C_n is the cost in year n, q is the discount factor, d is the expected real discount rate per annum, n is the number of years between the base date and the occurrence of the costs and p is the period of analysis.

The NPV represents the monetary sum that should be allocated at year 0 for future expenditure of an asset. Probably a more realistic way of ensuring the money is by yearly savings. This is not included in this thesis since it is just a comparison tool. In order to use it as a budgeting tool adjustments have to be made. The Equivalent Annual Costs can be used for this purpose.

2.3.1. PRESENT VALUE

For the NPV holds that it is "the present value of the cash inflows *minus* the present value of the cash outflows"(Averkamp, n.d.). In this thesis no cash inflows are taken into account and for that reason it is better to use the term Present Value (PV), which is "the result of discounting future amounts to the present"(Averkamp, n.d.). During this thesis the term Present Value (PV) will be used.

2.3.2. EQUIVALENT ANNUAL COSTS

Another method to compare LCC is the Equivalent Annual Costs (EAC). This method is particularly useful when the lifetimes of the assets that have to be compared are not the same. The EAC is calculated by dividing the (N)PV of the asset by the present value of annuity and represent the costs per year of owning and operating an asset over its entire lifespan. This is shown by equation (2.2).

$$X_{EAC} = \frac{\sum (C_n \cdot q)}{\alpha_{\overline{p}|d}} = \frac{\sum_{n=1}^{p} \left(\frac{C_n}{(1+d)^n} \right)}{\alpha_{\overline{p}|d}} \tag{2.2}$$

With $\alpha_{\overline{p}|d}$ is the present value of an annuity factor:

$$\alpha_{\overline{p}|d} = \frac{1-(1+d)^{-p}}{d} \tag{2.3}$$

Because within this thesis the assets both have the same lifetime the PV will be used. In the end also EAC values will be presented since these can be used for capital budgeting. Capital budgeting is "a process used by companies for evaluating and ranking potential expenditures or investments that are significant in amount"(Averkamp, -).

2.4. DISCOUNT RATE

To discount future costs or earnings a discount rate is used. For LCC purposes a *real* interest rate is used. This real interest rate consists of a real, risk free, interest rate and a risk addition. This section will shortly discuss both.

$$d = R + R_{risk} \tag{2.4}$$

With d is the real discount rate, R is the real, risk free, discount rate and R_{risk} is the risk addition.

2.4.1. REAL, RISK FREE, DISCOUNT RATE

The real discount rate can be calculated by subtracting the inflation rate from the nominal interest rate. The real discount rate is used to calculate the PV and is used to understand the true costs of a project over time.

$$R = N - I \tag{2.5}$$

With R is the real, risk free, interest rate, N is the nominal interest rate and I is the inflation rate. According to Rienstra and Groot (2012) this real, risk free, interest rate is 2,5% in the Netherlands. However, *Leidraad Kunstwerken* (2003) suggests a real, risk free, discount rate of 4% and claims that this is an agreed upon value within the government. The 2,5% is the more recent number and has been determined in 2007. The difference can be explained by changes in the economical situation over time.

Since the inflation rate is not included this PV cannot be used for budgeting purposes, the EAC however can be used for capital budgeting. By excluding the inflation rate the reliability for comparison usages increases since the inflation is very unpredictable. Between 1991 and 2014 an all time high of 5% and an all time low of -0,70% for the Euro have been registered (Trading Economics, 2014).

2.4.2. RISK ADDITION

To take risks into account the risk free real interest rate can be increased by a standard of 3% or by a specifically calculated risk addition for the project. This is usually done to discount future earnings by a higher discount rate which results in a lower PV. However, because this LCC only takes costs into account a higher discount rate would mean future costs become less important. This results obviously in lower total LCC. For this reason, and because of the low risks according to the available literature, a risk addition of 0% is proposed (Rienstra & Groot, 2012).

2.4.3. USED DISCOUNT RATE AND PRESENT VALUE OF ANNUITY FACTOR

The (expected) real discount rate during this thesis will be 2,5%, based on Rienstra and Groot (2012) and interviews.

$$d = 2{,}5\% \tag{2.6}$$

With this real discount rate the present value of annuity factor can be calculated:

$$\alpha_{\overline{p}|d} \approx 36{,}6 \tag{2.7}$$

2.5. COST GROUPS

The cost groups that should be taken into account according to ISO (2008) can be seen in figure 2.5. The definitions of these groups, as defined by presented by ISO, will be given in the following sections. Section 2.5.5 discusses the costs due to function loss of the asset, these are not included in ISO (2008), but they are included in *Leidraad Kunstwerken* (2003).

2.5.1. CONSTRUCTION COSTS

"*All costs included in acquiring an asset by purchase/lease or construction procurement route, excluding costs during the occupation and use or end-of-life phases of the life cycle and constructed asset.*"

The total construction costs will be assumed to take place at the end of year zero. The construction costs may be spread out over a few years, but a construction planning is required to determine which costs will happen at what moment. This is not within the scope of this thesis.

2.5.2. OPERATION (OR MANAGEMENT) COSTS

"*Costs incurred in running and managing the facility or built environment, including administration support services.*"

The operation (or management) costs are costs that are associated with the daily management of the asset. It is assumed that these costs will be very similar or the same for both barriers and for that reason they will not result in a differentiation in costs. Furthermore, they are assumed to be very small relative to the construction and maintenance costs. This means they can be excluded from the analysis for this purpose.

Management costs can also be included as a percentage of the maintenance costs. It has been chosen to not include them. They should be included for budgeting purposes.

2.5.3. MAINTENANCE COSTS

"*Total of necessarily incurred labour, material and other related costs incurred to retain a building or its parts in a state in which it can perform its required functions.*"

The maintenance costs are a very large part of the LCC for these kind of assets. Next to the construction costs the focus should be on getting a good idea of the maintenance costs and regimes. It will be assumed that all maintenance costs take place at the end of the year in which the maintenance takes place.

2.5.4. END-OF-LIFE COSTS

"*Net cost or fee for disposing of an asset at the end of its service life or interest period, including costs resulting from decommissioning, deconstruction and demolition of a building; recycling, making environmentally safe and recovery and disposal of components and materials and transport and regulatory costs.*"

Usually the end-of-life costs should be included in an LCC analysis. These may include costs for demolition and/or preparing the site after demolition or costs because of pollution of the area. Also end-of-life residual value may be taken into account. Because there is very little information available of the end-of-life costs for storm surge barriers it has been decided to not include them. Furthermore, it is reasonable to assume that the end-of-life costs for both barriers are comparable since they are both barriers designed for the same location and with comparable measurements. Lastly, end-of-life costs may be part of the construction costs, since it can be seen as preparing the location for a new asset. It must be noted that the end-of-life costs formally should be included and that it obviously improves the reliability.

Florida Department of Transportation (FDOT) (2014) shows construction and demolition costs per square foot for bridges in Florida (USA). Based on these figures can be said that for bridges hold that the demolition costs are about 30% to 35% of the construction costs for normal bridges. This reduces to about 3,5% for movable bridge spans. So the end-of-life costs could be taken as percentage of the construction costs.

2.5.5. FUNCTION LOSS COSTS

Leidraad Kunstwerken (2003) defines the total costs as follows:

$$C_{total,discounted} = \sum_{j=0}^{jl} \left(\frac{C_{acquisition}}{(1+r)^t} + \frac{C_{inspection}}{(1+r)^t} + \frac{C_{maintenance}}{(1+r)^t} + \frac{C_{management}}{(1+r)^t} + \frac{C_{function\ loss}}{(1+r)^t} \right) \tag{2.8}$$

with j is the year, jl is the year of the end of life, $C_{acquisition}$ are the costs for acquisition in year j, $C_{inspection}$ are the costs for inspection in year j, $C_{maintenance}$ are the costs for maintenance in year j, $C_{management}$ are the costs for management in year j and $C_{function\ loss}$ are the risk costs for function loss in year j.

These $C_{function\ loss}$ are risk costs and should be calculated by multiplying the probability of function loss by the costs of the consequences of this loss of function in year j, which is a commonly used definition for risk: Risk is probability times consequence (in Euro):

$$\text{Risk} = P_f \cdot \text{Damage} \tag{2.9}$$

These costs are very difficult to determine accurately, since not al failure probabilities can be found and the damage is dependent on the extremeness of the event, it has been chosen to not include them in the LCC analyses. Because they are very important and will probably differ, they will be discussed in chapter 9 in a qualitative way.

3

INFLATABLE DAMS

Within this chapter the background principles of an inflatable dam are discussed. First a brief overview of different barrier types will be given in section 3.1 and then the focus will be on inflatable barriers. In section 3.2 general aspects relevant for inflatable dams are discussed, namely the basic forms of inflatable dams, basic principles of inflatable barriers, fill material, flexible membrane and clamping. Section 3.3 will describe the reference case Ramspol and section 3.4 will discuss the inflatable barriers compared to traditional barriers and gives possible locations for a case study.

3.1. BARRIER TYPES

Before focussing on inflatable dams a short overview of different types of storm surge barriers will be given. The main function of storm surge barriers is to prevent flooding of the hinterland. A good definition of storm surge barriers is presented by De Vries (2014):

A storm surge barrier is a partly moveable(1) *barrier in an estuary or river branch which can be closed temporarily*(2)*. Its main function during surges is to reduce or prevent the rise of inner water level and thereby sufficiently*(3) *protecting the hinterlying area against inundation.*

1. The ratio of the cross section that is moveable must be large enough to be able to allow sufficient circulation flow in the inner water in normal conditions. This can for example be important for inner water ecosystems.
2. A temporary closure is defined as either (PIANC Working Group 26, 2006):
    - A closure required to protect against flooding starting from the moment of closing (related to expected high water levels) until the outer water level has dropped sufficiently. Overflow and increased inner water levels are taken into account.
    - A closure required to make the structure available for maintenance or repair.
3. Sufficiently regards the maximum allowable inner water level which, in turn, is influenced by river runoff and is determined by the height and safety standards of the dike ring behind the barrier.

Because every location is unique and requirements for storm surge barriers vary, no two barriers are the same. Every barrier built is designed especially for that location and its conditions. However, although there are no two barriers exactly the same, a few general types of barriers can be distinguished. Six general types of barriers are illustrated in figure 3.1.

The most suitable type of barrier should be determined after taken all factors into account. However, because this master thesis is specifically about inflatable barriers the procedure during this study will be the other way around.

Table 3.1 shows scores for these barrier types for several apects that are considered to be important for storm surge barriers. The table shows that there are a lot more aspects that should be considered besides the costs.

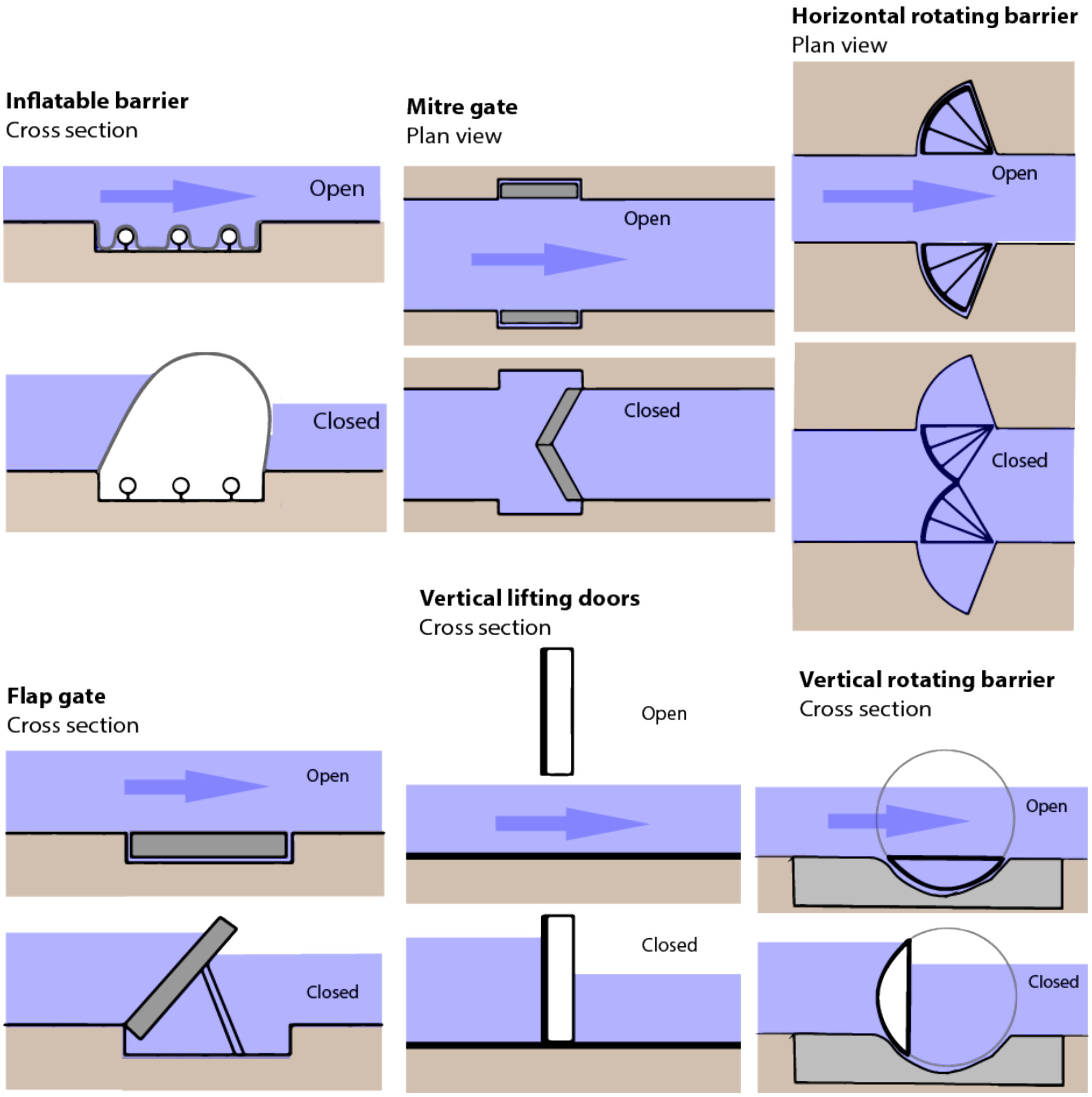

Figure 3.1: Illustrations of the basic types of barriers (based on Dircke et al. (2012))

It can be seen that inflatable barriers do not score very well according to Dircke et al. (2012). It must be noted that there is only little experience with inflatable storm surge barriers because only one inflatable dam has been built for this purpose. Also, contradicting information appears: Jongeling (2005) specifically claims that, compared to barriers with for example steel plates, little maintenance is required for inflatable barriers, this is contradictory to table 3.1. Furthermore, Van Breukelen (2013) investigated the possibility of scale enlargement of inflatable barriers and came up with a solution for a water depth of 15 m and a length of 210 m for the 3000 m wide inlet of Galveston Bay, while table 3.1 gives a negative score for these requirements.

Next to this, specific advantages of inflatable barriers are not taken into account. Examples are: an inflatable barrier is able to retain water in both directions and the loads are directly transferred to the foundation in stead of being transferred via abutments.

Disadvantages of an inflatable barrier are the limited ability to control the crest height and the downstream water level, problems with the storage of the membrane in the bottom recess, the relatively difficult replacement of the membrane and the vulnerability of the membrane to damages.

The scores for inflatable barriers in table 3.1 will be updated on the basis of findings during this research.

	Mitre gate	Vertical lifting	Flap	Horizontal rotating	Vertical rotating	Inflatable
Span > 30m	-	+	+	+	+	+
Span > 100 m	-	-	+	+	-	-
Water depth > 10 m	+	+	+	+	+	-
Impact upon landscape	+	-	+	+	-/+	+
Maintenance	+	+	-	0	+	0
Currents and waves	-	+	0	0/+	0/+	0
Closure time	+	+	+	+	+	0/-
Space required	+	+	+	-	+	+
Colliding ships	0/-	+	+	0/-	+	0
Reliability	-/+	+	0/+	-/+	+	0
Clearance height	+	-	+	+	-/+	+

Table 3.1: Comparison of the different barrier types: - Not favorable up to not feasible, 0/- Below average/vulnerable, 0 Average/possible, 0/+ Above average, + Favorable/proven technology, -/+ Score depends on design choices and conditions (Dircke et al., 2012)

3.2. GENERAL ASPECTS INFLATABLE DAMS

The information used in this section comes from Jongeling (2005) and Bouwdienst Rijkswaterstaat (2007).

3.2.1. BASIC FORMS

When discussing inflatable dams two basic variations can be distinguished.

1. Dams consisting of retaining bellows:
   These bellows are designed in such a way that they can retain water when they are inflated (see for example figure 3.3).
2. Dams consisting of supporting bellows combined with panels:
   Supporting bellows do not retain the water themselves but lift and support panels. The panels retain the water (see figure 3.2).

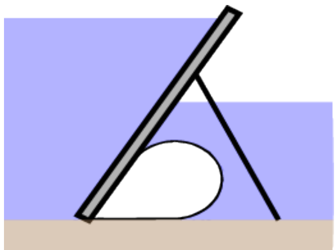

Figure 3.2: Supporting bellow

An example of supporting bellows is the Obermeyer Spillway Gate. An advantage of such a system is that the height of the flap can be controlled by in- or deflating the bellows. This allows a very precise water level management (Prett & Olson, 2010). However, within this study *retaining bellows* will be considered. Within the retaining bellows another important distinction has to be made between inflatable weirs and inflatable barriers.

INFLATABLE WEIRS

Inflatable weirs are designed to regulate water levels and/or discharges in rivers, basins and reservoirs and are almost always active. Because a weir usually only has to retain water in one direction a single row anchorage is sufficient.

As can be seen from figure 3.3, overflow is possible for weirs. Their function is to regulate the upstream properties, a superabundance of water may flow over the weir.

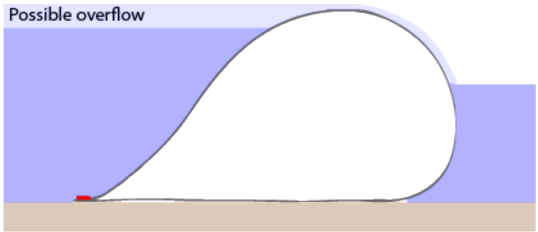

Figure 3.3: Single row anchored inflatable weir (inflated with air)

INFLATABLE BARRIERS (BELLOW BARRIERS)

Inflatable barriers on the other hand are only activated during high water (e.g. storm surges) and are inactive most of the time. Another function could be to retain polluted water. An important aspect of bellow barriers is that they usually have to be able to retain water in both directions. This also means that a double row anchorage is required.

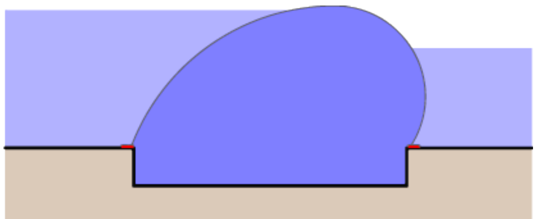

Figure 3.4: Double row anchored inflatable barrier (in this case filled with water)

Because this study is about the innovative use of inflatable dams as storm surge barriers the inflatable weirs will not be considered.

3.2.2. BASIC PRINCIPLE

The basic principle of an inflatable barrier is to close off an opening by inflating the bellow. Important aspects are the required height of the bellow, the allowable overtopping and maximum closure time. The bellow is usually inflated with air or water or a combination of them. To retain water, the pressure inside the bellow should be sufficiently high.

DIFFERENT STATES

For an inflatable barrier four different states can be distinguished:

1. Inactive
   This is the most common state for an inflatable barrier. The bellow is deflated and the water can flow freely through the opening. The membrane is stored under water in such a way that ships may pass without damaging the membrane.

2. Inflating
   When extreme water levels are expected or the water level exceeds a certain threshold level the bellow will be inflated. During this inflating water and/or air is pumped into the bellow and it slowly comes up. Depending on the fill material it closes like an upcoming weir or more like horizontal gates.

3. Inflated
   This is the active state of the barrier. The bellow is fully inflated and protects the hinterland from extreme water levels.

4. Deflating
   When the outside water level becomes lower than the threshold level the barrier can be deflated again. The filling material will be released from the bellow until it is completely empty. Then the membrane will be stored.

FORCE ACTION (INFLATED)

For bellows hold that, if they are loaded uniformly in the longitudinal direction and have uniform geometrical and strength properties, the hydraulic load will be transferred to the foundation uniformly. The loads follow the shape of the bellow to the clamps where they are transferred to the foundation. On the inside of the bellow works the internal (water- or air)pressure and on the outside water pressure is active. Usually the resulting pressure is acting outwards, for bellows filled with air locally the resulting pressure can be acting inwards (see figure 3.5). The shape of the bellow is such that for every part of the membrane the internal pressure, outside pressure, dead weight of the membrane and membrane forces are in equilibrium.

3.2.3. FILL MATERIAL

Bellows are usually filled with water, air or a combination. The fill material influences the design significantly. Some of the important aspects that are associated to the fill material are:

- The time it may take for the barrier to inflate
- The desired retaining height and required membrane length and internal pressure
- The magnitude of the forces acting in the membrane and on the foundation
- The expected dynamic behaviour of the barrier

One of the most important aspects for bellow barriers that is influenced by the fill material is the ability to inflate and deflate the bellow controlled.

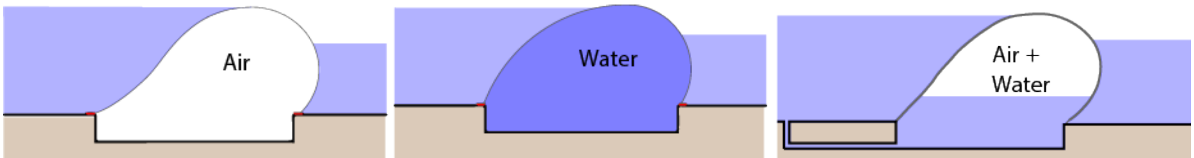

Figure 3.5: Three possible ways of filling an inflatable barrier

3.2.4. FLEXIBLE MEMBRANE

The membrane transfers the forces, resulting from internal pressure, external load and dead weight, to the foundation. The load is transferred by normal forces in the membrane. Important aspects for the membrane are strength, flexibility and resistance for fatigue. For this reason it is usually made of rubber which is reinforced with synthetic fibres. The main reinforcement is in the circumferential direction because the biggest loads are in this direction (normal forces). Some lateral reinforcement is also added. This reinforcement does not only increase the strength but also adds stiffness.

For the Ramspol barrier a membrane consisting of five layers is used, produced by Japanese manufacturer Bridgestone. The structure of the membrane is as follows (also see figure 3.6):

1. A rubber (Ethylene Propylene Diene Monomer (EPDM) component) with a thickness of 3 mm, able to resist water and the influence of UV-radiation.
2. A strengthening cloth in longitudinal direction (Polyamide 6 (PA6)), covered in two rubber layers 1,4 mm each.
3. A strengthening cloth in circumferential direction (PA6), covered in two rubber layers. This layer provides the main strength.
4. Same layer as layer 2.
5. A 2 mm thick rubber layer, also EPDM.

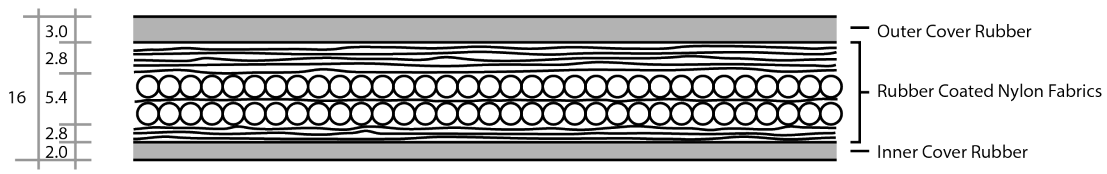

Figure 3.6: Membrane structure (measurements in mm)

A very important failure mechanism for the membrane appeared to be high temperatures in combination with being (partly) elevated above the water most of the time and being exposed to UV radiation and heat. One of the four rubber dams of the Tempe Town Lake dam suddenly failed after only 20 years because of this. The rubber membrane delaminated which is characteristic for Intra Carcass Pressurization (ICP) (Durkee, Ackerman, & Schweiger, 2013). Because inflatable barriers are deflated and stored under water almost always, it is assumed that this failure mechanism is unimportant. The solution for the Tempe Town Lake dam was to build a bridge over the bellows to protect them from heat and sun radiation.

3.2.5. CLAMPING

There are different techniques to connect the membrane and the foundation with clamps, see figure 3.7. A clamp is optimal if there is no weakening of the membrane due to the clamps. If a clamp is optimal, damage (tears) will occur outside of the clamp and the clamp efficiency is 100%.

The small wave I-clamp is used for the Ramspol barrier, because the manufacturer of the membrane uses this type. The efficiency is less than 100%, partly because the membrane has to be punctured by the prestressed bolts. The encirclement clamp gives almost 100% efficiency. More research is needed before the resin wedge clamp can be used.

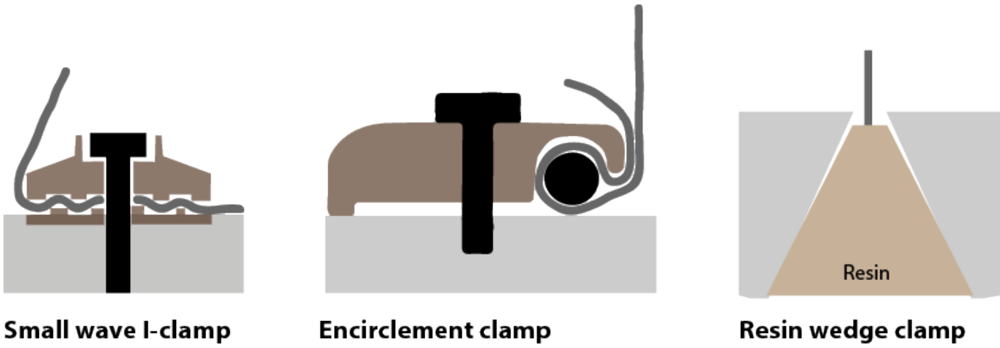

Figure 3.7: Three possible clamping mechanisms that can be applied

3.2.6. ALTERNATIVE WAYS OF STORAGE/INFLATING

An alternative option is to combine inflatable barriers and flaps (see figure 3.8). One of the advantages is storage. A disadvantage is that extra hinges are required. This system is used as emergency barrier in the Haarlemmermeer and currently maintenance works are taking place (Van Grootveld, 2014).

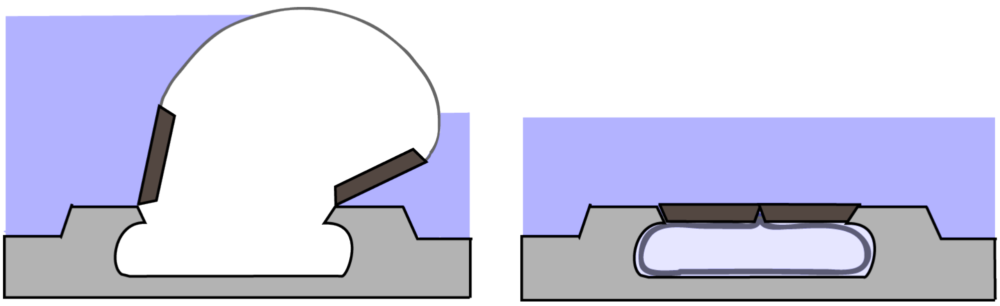

Figure 3.8: Alternative storage method used in the Haarlemmermeer

Another method is storage as it is proposed by Van Breukelen. She created extra storage as can be seen from figure 3.9. By using this method no rollers are required, but the force transfer from clamp to foundation is more difficult and probably heavy reinforcement is necessary.

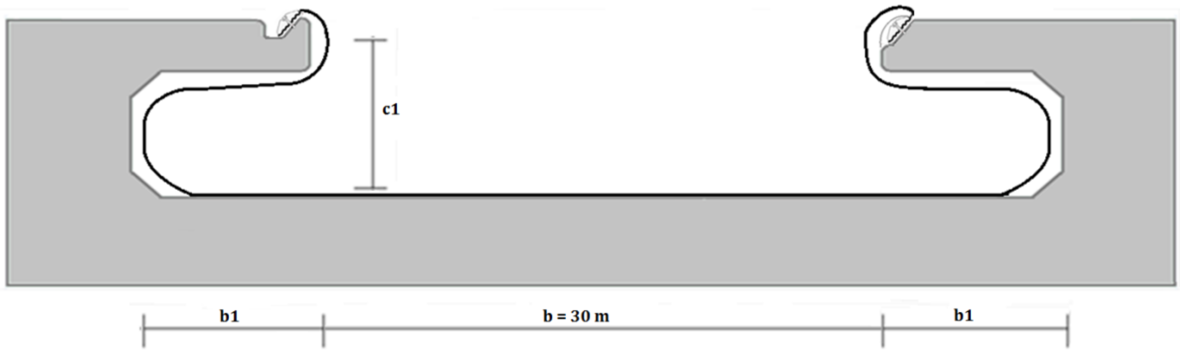

Figure 3.9: Alternative way of storing by creating extra storage space (Van Breukelen, 2013)

3.3. Reference case: inflatable barrier Ramspol

As a reference case for inflatable barriers the Ramspol barrier in the Netherlands will be used. This is the first and, until now, only inflatable dam that has been built as a storm surge barrier. This barrier is built to protect the area surrounding the "Zwarte Meer" from high water in the "Ketelmeer", see figure 3.10.

Figure 3.10: Location of inflatable barrier Ramspol in the Netherlands (Google Earth)

Some facts and figure for the structure that make it unique in the world (also presented in figure 3.11):

- The head during design situation is 4,4 m
- During design situation the water level at the side of Ketelmeer is 3,55 m + NAP
- Three bellows with the same dimensions:
  - A length of 80 m
  - A width of 13 m (in between the anchor rows)
  - A retaining height of 8,2 m
- Filled with both air and water
- Filling procedure takes 0,5 - 1 hour
- Maximum failure probability of $3{,}5 \cdot 10^{-3}$ per closure

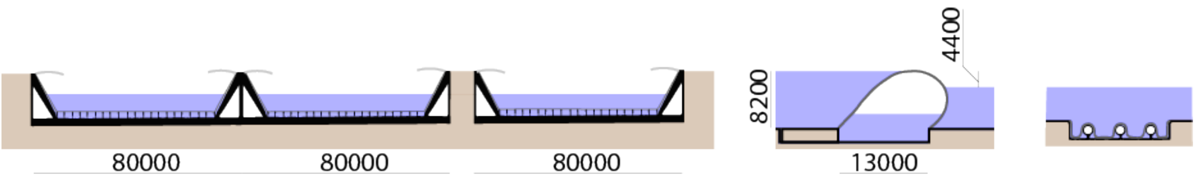

Figure 3.11: Sections for the Ramspol barrier, left gives a longitudinal section and right are the active and inactive cross-sections, all measurements are in mm

Jongeling claims that the Ramspol barrier functioned properly and according to the requirements until that moment (2005). Bouwdienst Rijkswaterstaat (2007) provides some extra insights and focus points, but no failures are reported. Both do not discuss the ship collision in 2004 that is mentioned in Horvat & Partners (2010). Main focus points suggested by Bouwdienst Rijkswaterstaat are:

- Extra inspections with a diver to check for sharp objects near the clamps
- Include sonar to check the position of the stored membrane
- Include a system that warns if the membrane is not stored properly

- Monitor the resistance of the rolls
- Check the pretension force in the bolts
- Monitor the costs during the lifetime to see if it is actually less costly than other options

Until now the barrier seemed to have worked without problems or failure. A disadvantage of the control system is that it measures the outside water level and acts on that measurements. It happened once that the barrier was inflated and deflated shortly after that, this created a translation wave reflecting between the barrier location and the opposing shore causing the barrier to close every time the wave was near the barrier.

3.4. INFLATABLE BARRIERS VERSUS TRADITIONAL BARRIERS

According to Bouwdienst Rijkswaterstaat (2007) one of the reasons for building the inflatable barrier at Ramspol was the expectation that it was going to be less costly than a traditional barrier. Van Breukelen (2013) concluded the same in the thesis about scale enlargement, but her cost calculations were very basic. Dirkmaat (2011) concluded that an inflatable barrier in the Spui (in the Netherlands) would be 4 to 25 times as expensive as other options for this location. It must be noticed that one of the main reasons for a structure in the Spui is to prevent salt intrusion. In order to make a well informed choice a cost comparison for the two barriers should be performed (amongst other analyses). Within this comparison not only acquisition costs should be taken into account, but the total life cycle costs. Chapter 2 already discussed the basic principles of Life Cycle Costing.

3.4.1. CASE STUDY

Before general conclusions can be drawn a case study is performed. A definition of a case study is:

"*An empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used*" (Soy, 1997).

This method is sometimes criticised since it is believed that a small number of cases cannot provide reliable conclusions. Others find it a useful exploratory tool (Soy, 1997).

Since LCC is a complex theory and there is no literature available for a LCC comparison between inflatable- and traditional barriers a case study is considered a very useful tool for this thesis. It provides a good starting point and insight in different aspects of LCC and can help to determine for example cost drivers. Based on those results more general conclusions can be presented.

POSSIBLE LOCATIONS FOR A CASE STUDY

Table 3.2 gives an overview of some of the characteristics for some barriers in the Netherlands and USA. Information for the Maeslant-, Hartel-, Eastern Scheldt-, Ramspol- and IHNC barrier follows from Van Ledden, Lansen, de Ridder, and Edge (2012). Welsink (2013) provides details for the Hollandse IJssel barrier and De Vries (2014) and Van Breukelen discuss the possibilities for the Bolivar Roads barrier.

According to Welsink (2013) the second Delta Committee concluded in 2008 that the Hollandse IJssel barrier does not provide sufficient safety anymore (taking sea level rise into account). This makes this barrier very interesting to consider first. However, for the Hartel barrier maintenance costs are available and the dimensions and requirements are quite similar compared to Ramspol. For these reasons it has been chosen to first focus on these two barriers (Hollandse IJssel and Hartel) as possible case study locations. Another approach could be to design, for example, a vertical lifting gate barrier at the location of the Ramspol barrier. The drawback of this would be that still only one design of an inflatable barrier would be available.

Storm Surge Barrier		**Type**	**Functions**							**Cost information available**
Name	Location		Allow river discharge	Professional shipping	Prevent salt water intrusion	Retain water in 2 directions	Retaining height > 10 m	Hydraulic head ≥ 5 m	Length > 250 m	
the Netherlands										
Maeslant	Hoek van Holland	Horizontal rotating	x	x			x	x	x	
Hartel	Spijkenisse	Vertical lifting doors	x			x		x		x
Eastern Scheldt	Kamperland	Vertical lifting doors	x	x		x	x	x	x	
Hollandse IJssel	Krimpen aan den IJssel	Vertical lifting doors	x	x	x	x	x			
Ramspol	Kampen	Inflatable	x	x		x				x
USA										
IHNC	New Orleans	Mainly sector gates		x		x	x	x	x	
Bolivar Roads	Galveston	- (no barrier yet)		x		x	x		x	

Table 3.2: Characteristics of some barriers that could be considered during this thesis. Note: all barriers must cope with shipping, but the Hartel- and Ramspol barrier do not have to allow professional shipping

HARTEL BARRIER

The Hartel Barrier can be seen as a traditional barrier because of the vertical lifting gates. However, the shape of the gates and the requirements make it an innovative design. The barrier is part of the Europoort Barrier (with the Maeslandt Barrier) and is located in the Hartel Canal near Spijkenisse (see figure 3.12). During storms its purpose is to protect South Holland when the Maeslandt Barrier closes off the Nieuwe Waterweg. During design conditions water may flow over the barrier. The gates have an elliptical shape, the towers are oval. Figure 3.13 shows schematised sections for the Hartel Barrier as it is built. The information and measurements follow from de Pagter (1996); I-Storm International Network (-); Linham and Nicholls (n.d.); Stichting Deltawerken Online (2005). The barrier is divided into two parts with different lengths because of the bridge pillar that was already present. The design head is 5,5 m. Note, the lock next to the gates is not considered here.

Figure 3.12: Location of the Hartel barrier in the Netherlands (Google Earth)

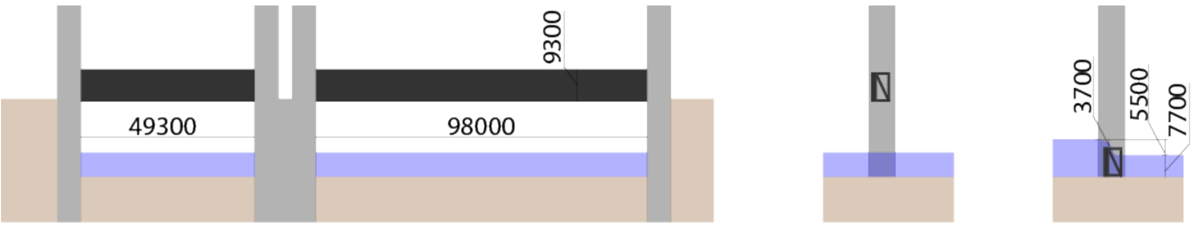

Figure 3.13: Schematised sections for the Hartel Barrier with the most relevant measurements [mm]. Left is the longitudinal section and right are two cross-sections, the most right figure represents the closed barrier with the design head.

HOLLANDSE IJSSEL BARRIER

The Hollandse IJssel barrier consists of two gates, one placed behind the other. It is located between Krimpen aan den IJssel and Capelle aan den IJssel in the Hollandse IJssel (see figure 3.14). In between the two gates a bridge is situated for cars and bikes. Also a lock is located next to the gates, this lock is not considered here. The function of the second barrier is to serve as backup for the first gate (Stichting Deltawerken Online, 2005). Sections of the gate are given by figure 3.15.

Figure 3.14: Location of the Hollandse IJssel barrier in the Netherlands (Google Earth)

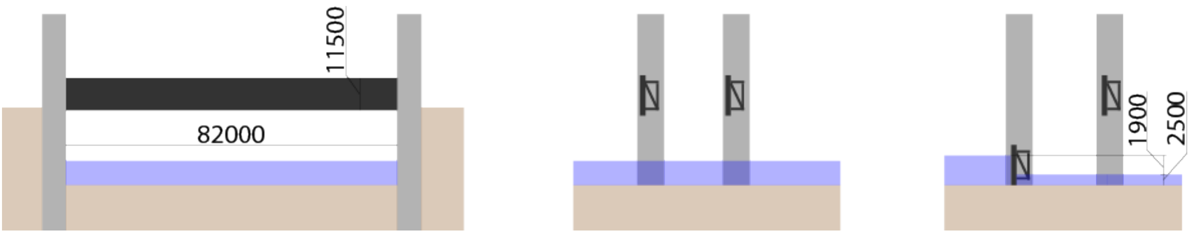

Figure 3.15: Schematised sections for the Hollandse IJssel barrier with the most relevant measurements [mm]. Left is the longitudinal section and right are two cross-sections, the most right figure represents the closed barrier with the design head. Note: the bridge, which is situated in between the two gates, is not shown here.

4

Design of the sheet

This chapter will discuss the design of the sheet and the shape of the bellow and forces in the membrane. Section 4.1 explains the theory that is used to calculate the forces in the membrane, section 4.2 calculates the external loads on the barriers and section 4.3 presents the first, conceptual designs for the Hartel-, Hollandse IJssel- and Ramspol barriers. Finally within sections 4.4 and 4.5 the final design of the barriers is discussed. Within these last two sections only the Hartel- and Ramspol barriers are discussed.

4.1. Pressures and forces on and within membrane

To be able to design a safe inflatable barrier, understanding of the mechanisms is very important. Within this section only barriers inflated by a combination of water and air are discussed (because this is the case for the reference project Ramspol). Three possible cases, depending on the internal water level relative to the downstream water level, are given by figure 4.1.

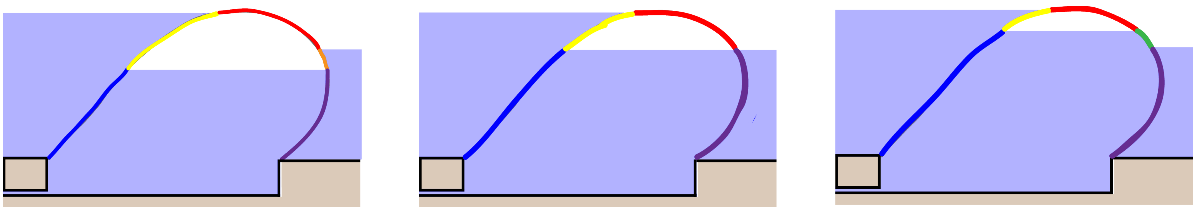

Figure 4.1: The six possible loading combinations on the membrane

The six possible membrane loads are given by table 4.1. For the meaning of the symbols see figure 4.6. Dorreman (1997) provides the basis for the resulting pressure formulas. Figure 4.2 shows an example of the method he used for a piece of membrane with water pressure on both the inside and the outside. The resulting pressures follow from this method. According to Bouwdienst Rijkswaterstaat (2007) the shape of the bellow is such that for every part of the membrane the internal pressure, outside pressure, dead weight of the membrane and membrane forces are in equilibrium.

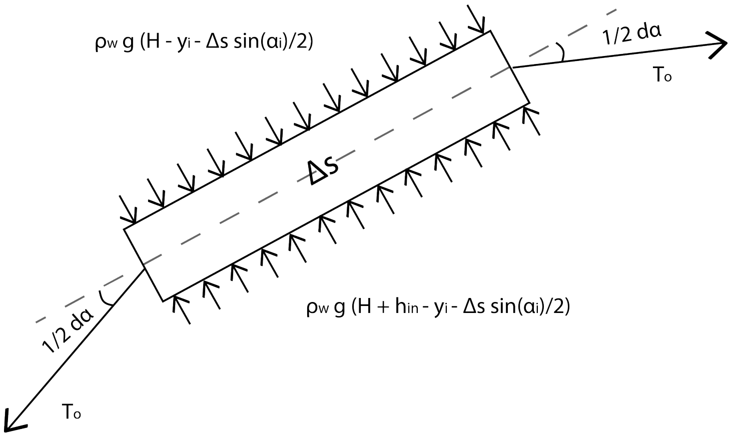

Figure 4.2: Piece of membrane (Δs) loaded by water pressure on both the inside and the outside (based on Dorreman (1997))

Color of membrane	Inside	Outside	Resulting pressure p
Blue	(Upstream[1]) water	Upstream water	$p = \rho_w g(H + h_{in} - h_1) = 0$[2]
Yellow	Air	Upstream water	$p = \rho_w g\left(H - h_1 + y_i + \Delta s \cdot \frac{\sin(\alpha_i)}{2}\right)$
Red	Air	Air	$p = \rho_w g H$
Orange	air	Downstream water	$p = \rho_w g\left(H - h_2 + y_i + \Delta s \cdot \frac{\sin(\alpha_i)}{2}\right)$
Green	(Upstream) water	Air	$p = \rho_w g\left(H + h_{in} - y_i - \Delta s \cdot \frac{\sin(\alpha_i)}{2}\right)$
Purple	(Upstream) water	Downstream water	$p = \rho_w g(H + h_{in} - h_2)$

Table 4.1: Loading combinations on the membrane. Resulting pressure formulas based on Dorreman (1997)

4.2. EXTERNAL LOADS

Within this section the external loads on the barriers will be discussed.

4.2.1. DATA

For the three barriers the external pressures acting on the barrier are determined. Figure 4.3 shows static water pressures, additional pressures due to waves and wind pressure.

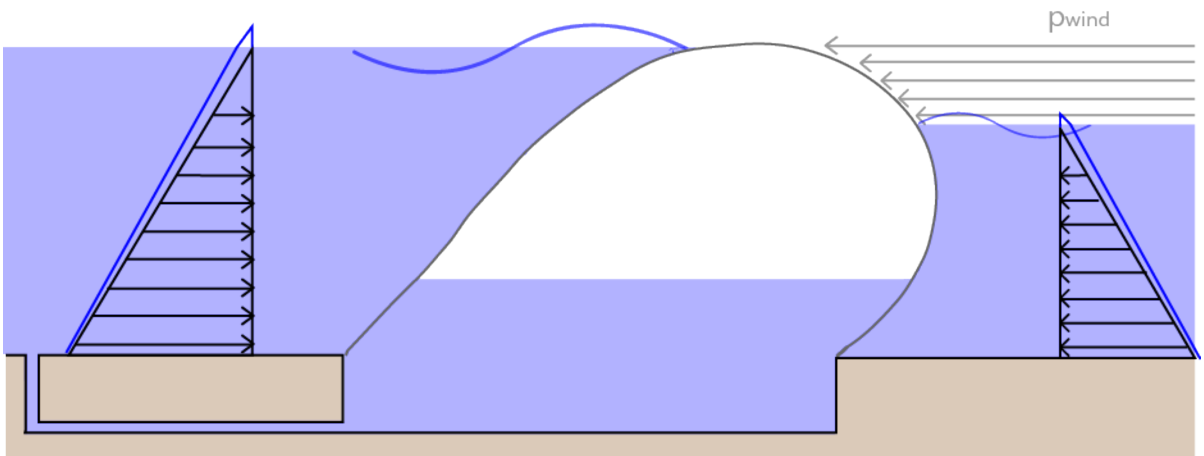

Figure 4.3: External loads acting on an inflatable barrier

To calculate the pressures, design conditions for the locations are needed, such as water levels, wave height

[1]Because of the opening outside water flows freely into the bellow like communicating vessels

[2]Resulting pressure is zero because of free inflow of upstream water, giving: $H + h_{in} = h_1$

and hydraulic head. Table 4.2 shows the design conditions for the Hartel-, Ramspol- and Hollandse IJssel barrier. Figure 4.4 explains the meaning of some of the symbols used in table 4.2. H_s is the significant wave height and T the period of the wave.

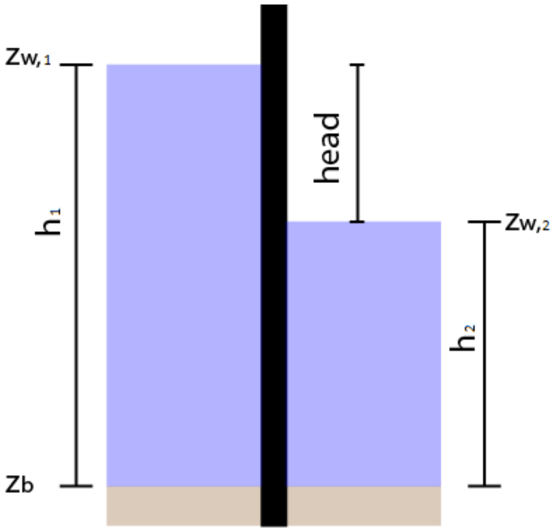

Figure 4.4: Schematised barrier (black rectangle) and explanation of symbols

	Ramspol	Hartel	Hollandse IJssel	Unit
$z_{w,1}$	3,55	6,7 [3]	4,4	NAP+m
$z_{w,2}$	-0,85	1,2	2,5	NAP+m
z_b	-4,65	-6,5	-6,5	NAP+m
h_1	8,2	13,2 [4]	10,9	m
h_2	3,6	7,7	9	m
head	4,4	5,5	1,9	m
H_s	2,6 [5]	0,6 [6]	1,18 [7]	m
T	4,1 [5]	3,1 [8]	3,92 [7]	s

Table 4.2: Design conditions for the Hartel-, Ramspol- and Hollandse IJssel barrier

If the wave period is not known, it can be estimated by making use of equation (4.1). This is a rough estimate based on Det Norske Veritas AS (DNV) (2011, section 2.2.6.7).

$$T_p \sim 4 \cdot \sqrt{H_s} \tag{4.1}$$

4.2.2. DESSIGN ASSUMPTION: OUTSIDE WATER LEVEL HARTEL BARRIER

It must be noted that it has been assumed that from now on overflow will not take place for the Hartel barrier. It is known that for this barrier holds that overflow will take place during design conditions. To make sure no overflow takes place it has been assumed that the maximum water level for the Hartel barrier is equal to the crest height of the gate: $h_1 = 9.5$ m and $z_{w,1} = \text{NAP} + 3$ m (see figure 4.5). The reason is that good design tools are available for a non-overflowing inflatable barrier. These tools do not work for inflatable barriers that allow overflow[9]. More information about the consequences can be found in section 5.2 and appendix E.

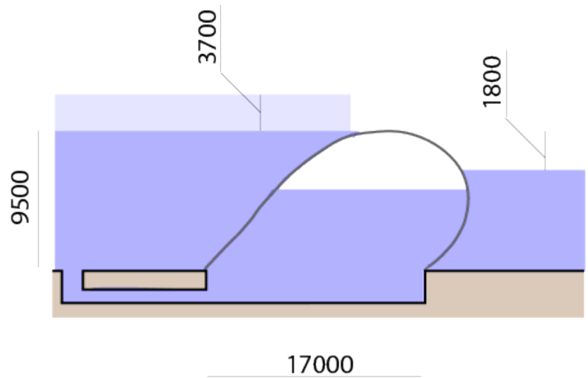

Figure 4.5: Illustration of the design assumption, it is assumed that the outside water height is 9,5 m, so the extra 3,7 m (in light blue) is neglected (all measurements are in mm)

[3] This is 3,7 m higher than the top of the gate; overflow is allowed
[4] The height of the gate is 9,3 m and a gap is of about 0,2 m is present at sill level (Dircke et al., 2012)
[5] Van Breukelen (2013)
[6] Van Vugt (2008)
[7] Welsink (2013)
[8] Estimated by using equation (4.1)
[9] The Excel spreadsheet prepared by Dirkmaat shows an error of more than 20 % which is too high, even for preliminary design purposes

4.2.3. CALCULATION OF FORCES

The calculation of the forces is split up in still water level, waves, and wind.

STILL WATER LEVEL

The water pressure for the still water level can be calculated by using the following equation:

$$p_{bottom,swi} = \rho g h_i \tag{4.2}$$

The force per meter barrier length can then be calculated by:

$$F_{sw} = \frac{1}{2} p_{bottom,swi} \cdot h_i \tag{4.3}$$

The results for the barriers are given by table 4.3.

	Ramspol	Hartel	Hollandse IJssel	Unit
h_1	8,2	9,5 [10]	10,9	m
h_2	3,6	7,7	9	m
$p_{bottom,sw1}$	80,4	93,2	106,9	kN/m^2
$F_{sw,1}$	329,8	442,7	582,8	kN/m
$p_{bottom,sw2}$	35,3	75,5	88,3	kN/m^2
$F_{sw,2}$	63,6	290,8	397,3	kN/m

Table 4.3: Pressures and forces due to still water levels

WAVES

Waves cause an additional pressure which is variable over time. According to prof. ir. drs. J. K. Vrijling et al. (2011) the maximum pressure caused by waves on a vertical wall can be described by linear wave theory as follows:

$$p = \rho g H_i \frac{\cosh(k(d+z))}{\cosh(kd)} \tag{4.4}$$

With H_i is the wave height (m) of an incoming wave and k is the wave number of the incoming wave $\left(k = \frac{2\pi}{L}\right)$)m^{-1}). To take into account that the reflection of the wave is less that 1 because most of the wave will go over the barrier this has to be adjusted to:

$$p = \frac{1}{2} \rho g H_r \frac{\cosh(k(d+z))}{\cosh(kd)} \tag{4.5}$$

With $H_r = (1+r)H_i$ and r is the reflection rate. The reflection rate for waves is about 30 % for the extreme situation when h_1 is equal to the crest height of the barrier (Jongeling, 2005). The force can be calculated by:

$$F_w = h_i \cdot p_{bottom} + \frac{1}{2}(p_{sw} - p_{bottom})h_i = \frac{1}{2}(p_{sw} + p_{bottom})h_i \tag{4.6}$$

The results for pressure and force for the upstream side are given by table 4.4. It is assumed that no relevant wave action is present at the downstream side due to the shelter of the bellow.

As can be seen the forces due to waves are about 15 % of the still water level force for the Ramspol barrier and less than 10 % for the other locations. Because it is necessary to do a Finite Element Method (FEM) analysis to include the dynamic loads from waves and because the contribution is relatively low, waves will not be considered during design. The dynamic effects are included by a safety factor later on.

WIND

Van Breukelen calculated the wind load for the Ramspol barrier to be 2 kN/m^2 and 8.8 kN/m. This is negligible compared to the loads due to water. Because of the small size of the load and the fact that wind loads are not included in the spreadsheet that is used to calculate the exact shape of the membrane, developed by Dirkmaat, wind loads are not included during the design phase.

[10] Note: this is not the same water level as in table 4.2 but a lower water level taken at the crest of the barrier, see section 4.2.2

	Ramspol	Hartel	Hollandse IJssel	Unit
H_s	1,5	0,6	1,18	m
T	4,1	3,1	3,92	s
H_i $(1.5H_s)$	1,5	0,9	1,77	m
r	0,3	0,3	0,3	-
H_r	2,0	1,2	2,3	m
p_{sw}	9,8	5,7	7,5	kN/m^2
p_{bottom}	2,5	0,2	0,8	kN/m^2
F_w	50,7	28,3	45,6	kN/m
$F_w/F_{sw,1}$	0,15	0,06	0,08	-

Table 4.4: Pressures and forces due to waves

4.3. ROUGH DESIGN

By using simple design rules for inflatable barriers based on the Ramspol experiences, a very good first estimate can be determined.

4.3.1. MEMBRANE FORCE CALCULATION

The tensile force in the membrane is determined by the internal and external pressures. It is possible to get a good first estimation of the force by using equation (4.9), which is derived from equations (4.7) and (4.8). Figure 4.6 shows the components of the equations.

$$H = \frac{1}{2}\rho g\left(h_1^2 - h_2^2\right) \tag{4.7}$$

$$H = -(RH_1 + RH_2) = T(\cos\phi_1 + \cos\phi_2) \tag{4.8}$$

$$T = \frac{\frac{1}{2}\rho g\left(h_1^2 - h_2^2\right)}{\cos\phi_1 + \cos\phi_2} \tag{4.9}$$

So, if it is assumed that the angles stay the same when the barrier is designed for the other locations, a good first estimate for the force in the membrane can be found by multiplying the membrane force for the Ramspol barrier by a factor ξ:

$$T_{\text{New location}} = \xi \cdot T_{\text{Ramspol}} \tag{4.10}$$

$$\xi = \frac{h^2_{1,\text{New location}} - h^2_{2,\text{New location}}}{h^2_{1,\text{Ramspol}} - h^2_{2,\text{Ramspol}}} \tag{4.11}$$

Table 4.5 gives the membrane force in the Ramspol barrier (Jongeling, 2005) and the expected membrane forces for the Hartel and Hollandse IJssel location based on this theory.

	Ramspol	Hartel	Hollandse IJssel	Unit
h_1	8,2	9,5	10,9	m
h_2	3,6	7,7	9	m
$h_1^2 - h_2^2$	54,28	31,0	37,81	m^2
ξ	-	0,57	0,70	-
T	250	142,6	174,1	kN

Table 4.5: First estimate membrane forces

4.3.2. DIMENSIONS

It is also possible to get a first idea about the dimensions of the barriers. According to Jongeling (2005), the following relations hold for the Ramspol barrier:

$$\begin{aligned} L &= 2.96 \cdot H \\ B &= 1.59 \cdot H \end{aligned} \tag{4.12}$$

With H is the crest height of the barrier, L is the length of the membrane and B is the width of the base (in between the two clamping lines). The results for the barriers can be found in table 4.6.

	Ramspol	Hartel	Hollandse IJssel	Unit
H	8,2	9,5	10,9	m
L	24,3	28,1	32,3	m
B	13	15,1	17,3	m

Table 4.6: First estimate of the dimensions

4.4. FINAL DESIGN SHEET (HARTEL LOCATION)

For the Hartel barrier maintenance costs are available and for that reason it will be considered first. *This means that the Hollandse IJssel barrier will not be included from now on.*

By using the spreadsheet created by Dirkmaat the final shape and forces on the barrier can be calculated. Table 4.9 shows the effect of changing input parameters on the output parameters. It has been assumed that it is preferable to end up with an "L" as small as possible because of cost considerations. The results for the Hartel location compared to Ramspol are given by figure 4.6 and table 4.8. Table 4.7 provides the input for the spreadsheet.

The Ramspol results are determined by using the same spreadsheet. Given the design conditions from Jongeling (2005, (p.3-19))[11] the tensile force calculated by the sheet is 230 kN/m^1, the report suggests a tensile force of about 250 kN/m^1. This is an acceptable difference. From now on the results given in table 4.8 will be used.

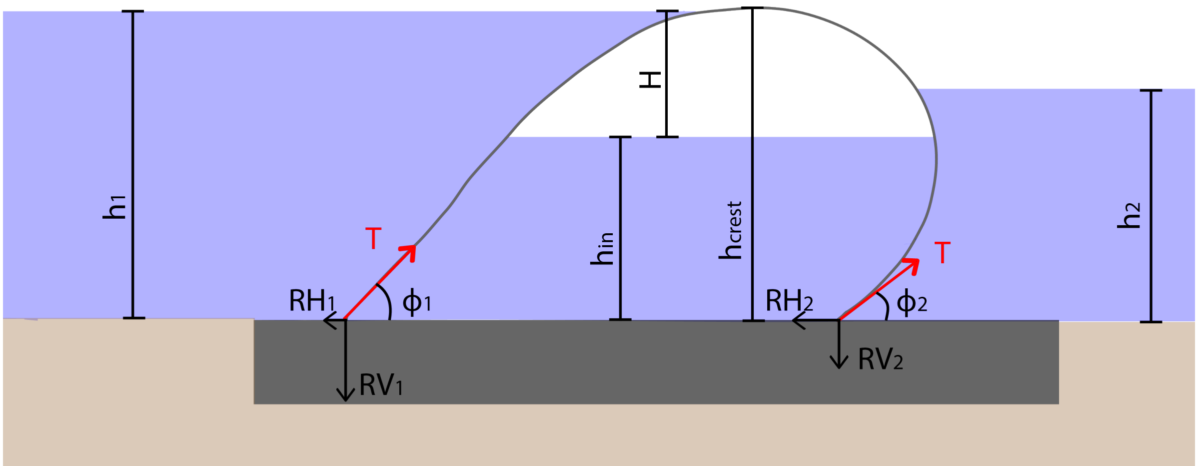

Figure 4.6: Location and direction of forces for inflated barrier

	Ramspol	Hartel	Unit
h_1	8,2	9,5	m
h_2	3,8	7,7	m
head	4,4	1,8[12]	m
h_{crest} (aim)	8,2	9,5	m
B	13	16	m
L	24	28	m
p_{air}	0,45	0,3	bar
h_{in}	3,7	6,5	m

Table 4.7: Input in spreadsheet

	Ramspol	Hartel	Unit
h_{crest}	8,26	9,79	m
$h_{crest} - h_1$	0,06	0,29	m
RH_1	129,9	98,5	kN
RV_1	190,7	115,2	kN
RH_2	128,1	52,5	kN
RV_2	191,9	142,1	kN
T	230,7	151,5	kN
ϕ_1	56,3	49,5	degree
ϕ_2	55,7	69,7	degree

Table 4.8: Final design Hartel compared to Ramspol

It must be noted that the predicted tensile force in table 4.5 for the Hartel location appears to be a good first estimate with an underestimation of about 6 % compared to the tensile force calculated by the spreadsheet. From this can be concluded that the design rules can be used for very quick first design uses.

[11] These are the conditions used for the probabilistic calculations. They are used here because Jongeling (2005) also provides the associated forces for this situation.
[12] Note: see section 4.2.2.

Change	**Effect on T**	**Effect on vertical clamping force**	**Effect on horizontal clamping force**
Increase h_1	Decrease	Decrease RV_1	Increase RH_1
		Decrease RV_2	Increase RH_2
Increase h_2	Decrease	-	Decrease RH_1
			Decrease RH_2
Increase L	Increase	Increase RV_1	Increase RH_1
		Increase RV_2	Decrease RH_2
Increase B	Increase	Increase RV_1	Increase RH_1
			Decrease RH_2
Increase P_{air}	Increase	Increase RV_1	Increase RH_1
		Increase RV_2	Increase RH_2

Table 4.9: Influence of changing input parameters on output (based on van Breukelen (2013))

4.5. ACTUAL DESIGN FORCE MEMBRANE

The calculated tensile forces in the membrane are the forces in an undisturbed region due to static loads. To take dynamic effects and peak stresses due to clamping and folds into account coefficients must be included (Bouwdienst Rijkswaterstaat, 2007).

4.5.1. JAPANESE STANDARD

According to Van Breukelen (2013) the Japanese Standard uses a factor 9 between the static loads (calculated in a 2-D cross section) and the initial design tensile strength. However, during the design of the Ramspol barrier it was found that this factor cannot be extrapolated and further research was required. For Ramspol the following design formula was found:

$$R_d = \frac{R_t \cdot SCF_{test}}{\gamma_{mat}} \geq F_d = \gamma_{dyn} \cdot SCF \cdot F_{stat} \tag{4.13}$$

Finally the safety factor between the initial dry tensile strength of the membrane (1870 kN/m) and the static force in a 2-D cross section (200 kN/m) turned out to be about 9 (Bouwdienst Rijkswaterstaat, 2007).

A unit check can provide information about the safety in a very clear way. The unit check is shown in equation (4.14).

$$\frac{R_d}{F_d} \geq 1{,}0 \tag{4.14}$$

The higher the unit check, the more safety is within the asset.

4.5.2. CIRCUMFERENTIAL DIRECTION

Within this section the results of the calculations will be discussed. The calculations can be found in appendix E. The results of the calculations for the inflatable Hartel barrier for circumferential direction are given by table 4.10. R_d represents the design resistance or strength of the membrane and F_d represents the design force in the membrane.

	Middle section	**Downstream side**	**Upstream side**	**Joints**
R_d (kN)	840	1091	1091	947
F_d (kN)	197	636	719	594
R_d/F_d	4,27	1,71	1,52	1,59

Table 4.10: Resulting design force and strength in circumferential direction for inflatable Hartel barrier, full calculation can be found in appendix E

4.5.3. LONGITUDINAL DIRECTION

For the longitudinal direction holds that the force, and therefore the strength, usually is a lot less. The results of the calculations are given by table 4.11. The calculations can be found in appendix E.

	Ramspol	Hartel
R_d (kN)	355	355
F_d (kN)	338	192,4
R_d/F_d	1,05	1,85

Table 4.11: Results design force and strength in longitudinal direction, full calculation can be found in appendix E

5

FULL DESIGN FOR THE INFLATABLE HARTEL BARRIER

Within this chapter the other important design aspects for the inflatable barrier at the Hartel location will be discussed. Because the subject of this thesis is an LCC comparison, the design of an inflatable barrier is only a tool for a good comparison, for this reason during the design phase assumptions and decisions are made qualitatively mostly. Parts of the design will be a scaled version of Ramspol based on the boundary conditions in stead of a full design for this location.

5.1. NUMBER OF BELLOWS

The Hartel barrier currently consists of 2 gates with different lengths, having a combined length of about 150 m (see figure 3.13). The reason for the two gates and their lengths is a bridge pillar (from the Hartel bridge) that was already present, the same abutment is used for the barrier. Van Breukelen showed that bellows with a length of 210 m are feasible, this means that theoretically the Hartel Canal can be closed with just one bellow. Four different options to close the total 150 m are considered:

1. Three bellows, all three have the same length of about 50 m (same as Ramspol concept)
2. Two bellows, both bellows have the same length of about 75 m
3. Two bellows, one with a length of about 50 m and one with a length of about 100 m (same as current Hartel concept)
4. One bellow with a length of about 150 m

These four concepts are compared in table 5.1. And the reasoning is given in the following sections.

	Three bellows $L_{1,2,3} \approx 50$ m	Two bellows $L_{1,2} \approx 75$ m	Two bellows $L_1 \approx 50$m $L_2 \approx 100$ m	One bellow L $\approx$ 150 m
Abutments	-	-	+	++
Membrane	+	+	-	+
Safety	++	+	+/-	−
Installations	- -	+/-	+/-	+
Comparability	-	+/-	++	- -
Inflation time	++	+	+/-	-
Maintenance	++	+	+	-
Shipping	- -	-	+/-	+/-

Table 5.1: Comparison of the four bellow concepts, ++ is the best score, +/- is average and - - is the lowest score

Abutments
Within this requirement the number and the location of the abutments is taken into account. Abutments are a great cost factor and for this reason the lower the number of abutments needed, the better the score. Next to this, one of the advantages of an inflatable barrier is supposed to be the possibility of closing great lengths without abutments. Also the location of the abutments is important because of the presence of the bridge pillar. If an abutment is necessary, placing it at the same location as the bridge pillar is highly recommended. Reasoning for the scores for the four concepts:

1. The three bellow (Ramspol) concept scores a minus because the highest number (four) of abutments is necessary. However, using three bellows with the same length results in one abutment at the same location of the bridge pillar, which is preferable.

2. Two bellows with the same length result in the need of three abutments. However, because of the location of the abutment, in the middle of the canal 25 m from the bridge pillar, a minus has been given since this is inadvisable.

3. Using the same division as for the Hartel barrier scores a plus, mainly because of the location of the middle abutment at the location of the bridge pillar.

4. The highest score for this requirement is given here because the least amount of abutments is needed. The absence of an abutment at the location of the bridge pillar is no disadvantage.

Membrane
This requirement is mainly about the different lengths of the membrane. The main reason for the Ramspol barrier to use 3 bellows is the wish to have three bellows with the same length. For this reason concepts 1, 2 and 4 get a plus and concept 3, with two different bellow lengths, gets a minus. Because the impact of having different lengths is not that big, no ++ and - - are awarded.

Safety
By safety, the ability to provide protection when one of the bellows fails or is damaged is meant. The longer the bellow the bigger the problems when the bellow fails. Concept 3 (with two bellows with different lengths) has been given a neutral score since it is the same risk as the current situation. Having one bellow obviously results in the biggest risk and having more bellows with less length scores better.

Installations
Installations, like pumps, generators, etc., are expensive. Every bellow is inflated by its own system, so the more bellows, the more installations are needed. Although a longer bellow results in installations with a higher capacity, this is preferred because it is assumed that less installations with a higher capacity are less costly than more installations with a lower capacity.

Comparability
Comparability is meant as the ability to compare the new inflatable barrier and the existing Hartel barrier. For this reason concept 3 scores well, concept 2 scores neutral and concept 1 and 4 score poorly.

Inflation time
It seems reasonable to assume that inflation time increases by increasing the length of a bellow. This can partly be resolved by increasing pump capacities, but it is assumed that an effect is always present. Concept 3 scores less than concept 2 because of the presence of one bellow with a length of 100 m.

Maintenance
Because maintenance in the dry is highly recommended, part of the Hartel Canal is closed during maintenance operations. The one bellow concept scores the most negative score because the total Hartel Canal should be closed during maintenance. This is an unwanted situation because of shipping through the canal. The scores are determined by the maximum part of the canal should be closed during maintenance.

SHIPPING

The last criterion is shipping since this is one of the functions of the Hartel barrier. The lowest possible score of - - has been given to the concept one with three bellows and openings of 50 m because this is too narrow for the biggest ships. The concept with two bellows, each with a length of 75 m, is given a minus because the opening for ships will be smaller than the current Hartel barrier provides. For this reason concepts three and four score neutral since they both allow for a shipping opening of 100 m. The one bellow concept does not score better because it does not increase the width of the opening since the bridge pillar will still be present.

5.1.1. CONCLUSION NUMBER OF BELLOWS

From table 5.1 can be seen that concepts one to three score about the same. Because this thesis is about an LCC comparison the comparability requirement is taken to be very important. For this reason concept three, the same as the original Hartel barrier with two bellows with different lengths, will be used during this thesis.

5.2. MEMBRANE

In section 4.5 the design forces and strength for the membrane have been calculated and the unit check has been performed. These unit checks are again presented in table 5.2, this table also provides Δ values. These represent the extra safety margin which is present at the Hartel location compared to the Ramspol location:

$$\Delta = \left(\frac{R_d}{F_d}(\text{Hartel}) - \frac{R_d}{F_d}(\text{Ramspol})\right) \cdot 100 \tag{5.1}$$

As can be seen from table 5.2 the extra margin for the Hartel location is at least 52%. From this information can be concluded that a less costly membrane with less capacity could be used. However, because the membrane forces are calculated for a decreased upstream water level (see section 4.2.2) and because overflow is not taken into account it has been decided to use the same membrane that is used for Ramspol. This membrane insures an extra safety to take these extra loads into account.

	Ramspol	Hartel	Unit
R_d/F_d (circ.)	1,00	1,52	-
Δ_{circ}	-	52	%
R_d/F_d (long.)	1,02	1,78	-
Δ_{long}	-	76	%
Total area	6500[1]	4750[2]	m^2

Table 5.2: Design forces in membrane for Hartel and Ramspol barriers (ULS)

The membrane of the Ramspol barrier has already been discussed in section 3.2.4. Appendix E provides an analysis to check whether this extra safety is enough.

5.3. ABUTMENTS

Van Breukelen showed that if leakage is allowed, inflatable bellows without abutments can be used. For the Hartel location leakage can obviously be allowed, to a certain amount, because the Hartel barrier works as a weir during extreme water levels. Which means that water flows over the barrier anyhow. An advantage of this approach, without abutments, is that the barrier can be designed in such a way that no or just small folds in the membrane will be present. Folds are the main reason for peak stresses in the membrane, so not having folds would be a great advantage. Another advantage is that when the barrier is inactive it is totally invisible.

However, Ramspol was built with abutments and all available documentation and costs are based on that. Also, at this location it is not that important to build a completely invisible barrier. For that reason, the first design will make use of abutments. The option of building an inflatable barrier without abutments will be discussed in chapter 9.

[1] $A = 3 \times 90 \cdot 24 \text{ m} \approx 6500 \text{ m}^2$
[2] $A = (110+60) \cdot 28 \text{ m} \approx 4750 \text{ m}^2$

5.4. FOUNDATION

Table 4.8 provides the horizontal and vertical forces on the foundation for the Ramspol and Hartel barrier. Based on these figures the foundation for the inflatable Hartel barrier will be a scaled version of the Ramspol foundation. This is only possible if the soil conditions are similar. Appendix F shows that it is reasonable to assume that the soil conditions are similar. The concrete part of the foundation will be almost similar to the Ramspol version, the width must be slightly increased because a larger base width is used for the Hartel location. Furthermore, because of the bigger length of the membrane more rollers should be installed to be able to store the membrane. This is possible because of the larger width.

For Ramspol the forces are transferred to the ground by foundation piles under an angle. The costs for the foundation will be based on unit costs for the Ramspol foundation in €/kN.

5.5. BED PROTECTION

For the design of the membrane an outside water level equal to the crest level of the gates is used. However, it is known that outside water levels may be bigger and overflow can take place. This overflow was the main reason for the heavy bed protection that has been built for the Hartel barrier since it cause turbulence downstream of the barrier. Because it is not within the scope of this thesis to design a full bed protection for the inflatable Hartel barrier, the bed protection for the original Hartel barrier will be used. It must be noted that the bed protection should probably be adapted slightly because of the following reasons:

- The original Hartel barrier is sharp crested while the inflatable Hartel barrier is rounded which might change the location with the highest impacts
- During inflation of the inflatable Hartel barrier it will close as a combination of closing horizontal gates and an upcoming weir resulting in the appearance of a V-notch. This makes it likely that there will be a specific location for the bed protection with the highest loads. This V-notch is not present at the original Hartel barrier.
- The way of closing is different for both barriers: the original Hartel barrier closes by lowering the steel doors, this will result in a decreasing flow opening and increasing flow velocities until the doors are down. The inflatable Hartel barrier will come up from under water so the water will flow over the bellow and form a jet stream at some point.

Using the bed protection of the original Hartel barrier will give a very good first estimation of the costs for the bed protection in case of an inflatable barrier at that location

5.6. INSTALLATIONS

For the installations the volumes of water and air needed to inflate the bellows are important. During inflation air needs to be pumped into the bellow and water can flow in freely. However, during deflation the air can escape freely and the water has to be pumped out. From table 5.3 can be seen that the volume of air needed to inflate the Hartel barrier is about 63 % of the volume of air needed to inflate the Ramspol barrier. Also, the air pressure for the Hartel barrier is lower. From this can be concluded that, if water can flow in fast enough, the pump capacity required for air can be less without increasing the inflation time of 60 minutes. To ensure a deflation time less than 120 minutes a larger pump capacity is needed to pump the water out of the bellow because the volume of water within the barrier is almost twice as large. It will be assumed that the installations depend on the combined volumes of air and water that is needed to inflate the barrier.

	Ramspol	Hartel	Unit
Air	37.5	23.45	m^3/m^1
	9000	3517.5	m^3
	44.19	21.03	%
Water	47.36	88.03	m^3/m^1
	11366.4	13204.5	m^3
	55.81	78.97	%

Table 5.3: Comparison of volumes water and air in both barriers

The difference in percentages of water and air comes from the fact that the inside (or low-water side) water level is higher for the Hartel location compared to the Ramspol location. The water level within the bellow is about similar to the inside water level[3], so a lower head and higher inside water level results in a higher percentile volume of water.

5.7. GROUNDWORK

The groundwork includes the excavation of the building pits, constructing adjacent levees, dump pits for excavated soil and some abutments. Since Ramspol needed adjacent levees, a new dump pit for excavated soil, work on the leveel between Ramgeul and Ramsdiep and a large abutment the costs are expected to be much higher than for the Hartel barrier. More information can be found in appendix G and section 6.2.1.

5.8. FINAL DESIGN OF THE INFLATABLE HARTEL BARRIER

The final design for the inflatable Hartel barrier consists 2 bellows, with lengths of about 100 and 50 m. This is the same division as is used for the original Hartel barrier and by that increases the comparability of the two barrier types. Sections for the barrier, in active and inactive phase, are given by figure 5.1. It can be seen that no overflow is taken into account (the actual water level is shown in light blue). This has been accounted for by using a significantly over-designed membrane (also see appendix E). The foundation will be very similar and just a scaled down version of the Ramspol foundation. For the bed protection the same bed protection, as is used for the original Hartel barrier, will be used. This is necessary because of the high turbulence which is expected due to the overflow.

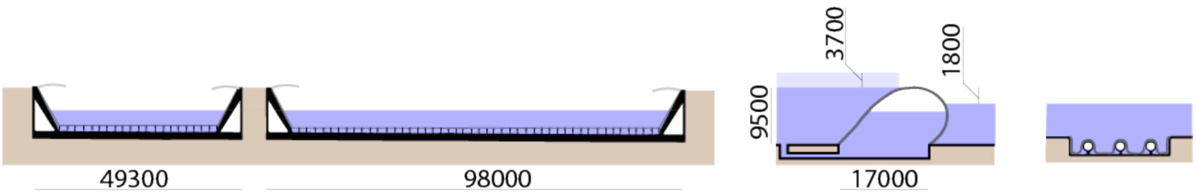

Figure 5.1: Sections for the inflatable barrier at Hartel location with dimensions in mm

[3]For the inflatable Hartel barrier this water level is lower than the inside water level due to cost considerations but still relatively high compared to Ramspol

6

Construction costs

This chapter will discuss the construction costs for the Ramspol barrier. These costs will be used to get a good impression of the construction costs for the inflatable barrier at the Hartel location. In the end also the construction costs for the original Hartel barrier are presented.

6.1. Construction costs Ramspol

The construction costs for the Ramspol barrier were about € 48.1 million (106.1 million guilders) in 1997[1]. For the new barrier the actual costs of the Ramspol barrier will be used. These costs will be used as the basis to estimate the construction costs for an inflatable barrier in the Hartel Canal. In order to do this the costs have to be regrouped.

6.1.1. Grouping of costs

In chapter 5 the design aspects are discussed. These will form the basis for the main costing groups because the costs can than be translated to the new barrier in an easy and clear way. The (main) groups and the approach of their unit costs are:

- Membrane:
  Because the same membrane structure is used for both barriers it is assumed that the only important aspect is the area of membrane needed.
- Abutments:
  The costs for the abutments are divided by the number of abutments in order to come up with a price per abutment. It is assumed that every abutment has the same construction costs.
- Foundation/Bottom recess:
  The foundation is assumed to be only dependent on the total forces of the membrane on the foundation during design conditions. By doing this an estimation of the costs can be based on the price per unit of force.
- Bed protection:
  The bed protection is kind of a problem because only light bed protection needed for the Ramspol barrier. However, the Hartel barrier works as a weir during design conditions resulting in significant turbulence downstream. For this reason a heavy bed protection is constructed downstream of the barrier. It is assumed that the exact same bed protection will be used for the inflatable barrier as is used for the original one.
- Installations:
  The installations are assumed to be dependent on the volumes of water and air that have to be pumped in and out of the bellows. A unit price per m^3 filling is used. This is very rough since water may flow into the bellow freely and the pumps are only needed to pump the water out of the bellow. The exact

[1] Information provided by BAM

opposite holds for the air; pumps are needed to pump air into the bellow, but can be released without pumps by valves.

- Groundwork:
  Groundwork for Ramspol included a lot of work , for an overview see appendix G. For the Hartel barrier it mainly consisted of the excavation of the building pits.

The inflatable Hartel barrier is designed based on this distribution. In order to predict the construction costs for the new inflatable barrier the costs for the Ramspol barrier should be translated into these groups. After doing this about 56 % of the total construction costs is defined. The remaining costs are divided into two groups:

- Risk, profit and unforeseen:
  Usually these are a percentage of the total sum. For that reason they can be treated separately. For the Ramspol barrier they are 18 % of the total costs and 31 % of the costs of the above groups.

- Other:
  This group is more vague. It includes costs that have to do with research, overhead, preparations and man hours. These costs are also assumed to be a fixed percentage of the total costs. For Ramspol this group is 25 % of the total costs and 44 % of the costs of the new groups.

The costs per group and their percentage of the total costs are given in table 6.1.

	Cost (€)	
Membrane	10.600.000	22%
Abutments	4.500.000	9%
Foundation	2.400.000	5%
Bed protection	1.400.000	3%
Installations	3.400.000	7%
Groundwork	5.200.000	11%
Risk, profit, unforeseen	8.500.000	18%
Percentage relative to main groups		*31%*
Other	12.100.000	25%
Percentage relative to main groups		*44%*
Total sum	**48.100.000**	

Table 6.1: Total construction costs Ramspol per group (1997 price level)[2]

This information will be used to make a good estimation of the costs of the inflatable barrier.

[2]Based on information provided by BAM

6.2. CONSTRUCTION COSTS INFLATABLE HARTEL

With the information found in the previous section the construction costs for the new inflatable barrier can be estimated. This section will discuss this process per cost group. Per group a unit cost is determined and this is used to calculate the costs for the inflatable Hartel barrier.

6.2.1. MAIN GROUPS

MEMBRANE

As already suggested, the costs for the membrane are related to the area of membrane needed. This area is the product of the length of the bellow in cross-sectional direction (see "L" in table 4.7) and the length of the barrier in longitudinal direction (L_{long}). However, because of the sloped ends at at both sides of the bellow, just using the length of the barrier in longitudinal direction is not enough, the extra length has to be included. For Ramspol every bellow has an additional 10 m of longitudinal length to compensate for the slopes, this will also be used for the new barrier. With this information the required area of the membrane can be calculated:

$$A_{\text{membrane}} = L_{\text{cross}} \cdot L_{\text{long}} = L_{\text{cross}} \cdot (L_{\text{barrier}} + 10 \cdot n) \tag{6.1}$$

With n is number of bellows and A_{membrane} in m^2 [3]. The results can be found in table 6.2.

Ramspol			Inflatable Hartel		
Total costs Ramspol	10.600.000	€	Unit costs Ramspol	1.631	€/m2
Area Ramspol	6.500	m2	Area Hartel	4.750	m2
Unit costs Ramspol	1.631	€/m2	Total costs Hartel	7.700.000	€

Table 6.2: Membrane costs Ramspol and new Hartel barrier (1997 price level)

ABUTMENTS

For the abutments a unit cost per abutment has been derived. Ramspol has a total of five abutments[4]. The Hartel barrier will have four abutments, because only 2 bellows will be used. This gives for the abutments:

Ramspol			Inflatable Hartel		
Total costs Ramspol	4.500.000	€	Unit costs Ramspol	900.000	€/p
Number of abutments Ramspol	5	p	Number of abutments Hartel	4	p
Unit costs Ramspol	900.000	€/p	Total costs Hartel	3.600.000	€

Table 6.3: Abutment costs Ramspol and new Hartel barrier (1997 price level)

FOUNDATION

The unit cost for foundation is derived per unit of force. For Ramspol the total force transferred from the membrane to the foundation is 642 kN. For the inflatable Hartel barrier the transferred total force is only 408 kN (see table 4.8). This results in:

Ramspol			Inflatable Hartel		
Total costs Ramspol	2.400.000	€	Unit costs Ramspol	3.741	€/kN
Total force at anchors	642	kN	Total force at anchors	408	kN
Unit costs Ramspol	3.741	€/kN	Total costs Hartel	1.500.000	€

Table 6.4: Foundation costs Ramspol and new Hartel barrier (1997 price level)

Another important aspect is the soil conditions at both locations. For both locations hold that the soil predominantly consist of clay and for this reason can be taken similar. More information about the soil conditions can be found in appendix F.

[3] For Ramspol: $A_{\text{membrane}} = (240 + 3 \cdot 10) \cdot 24 \approx 6.500\ m^2$
[4] The abutment in the middle of Ramsgeul is treated as 1 abutment

BED PROTECTION

These bed protection costs are based on the Ramspol costs. However, because overflow is allowed at the Hartel location, a heavier bed protection is probably required. The bed protection costs will finally be based on the costs of the bed protection for the Hartel barrier. Table 6.5 gives the bed protection costs if they were based on the Ramspol barrier and table 6.6 gives the costs for the costs for the bed protection for the original Hartel barrier. These costs are transformed to the 1997 price level to make them comparable (see section 6.3.2).

Ramspol			**Inflatable Hartel**		
Total costs Ramspol	1.400.000	€	Unit costs Ramspol	5.833	€/m
Length	240	m	Length Hartel	150	m
Unit costs Ramspol	5.833	€/m	Total costs Hartel	900.000	€

Table 6.5: Bed protection costs Ramspol and new Hartel barrier based on Ramspol bed protection (1997 price level)

Hartel		
Costs bed protection Hartel barrier (1996)	5.900.000[5]	€
Costs bed protection Hartel barrier (1997)	6.000.000[6]	€

Table 6.6: Bed protection costs Hartel barrier

INSTALLATIONS

For the installations the volumes of water and air that have to be pumped in or out of the bellows is important, these can be found in table 5.3. It has been assumed that the total volumes are the only relevant parameter. This results in the following costs:

Ramspol			**Inflatable Hartel**		
Total costs Ramspol	3.400.000	€	Unit costs Ramspol	167	€/m3
Volumes water + air	20.366	m3	Volumes water + air Hartel	16.722	m3
Unit costs Ramspol	167	€/m3	Total costs Hartel	2.800.000	€

Table 6.7: Installations costs Ramspol and new Hartel barrier (1997 price level)

GROUNDWORK

For the Ramspol barrier a lot of extra groundwork was required. This was due to (except from the soil excavation for the barrier) the abutment in between Ramsgeul and Ramsdiep, the two levee bodies adjacent to the barrier, the construction for the pit in the Ketelmeer to dump excavated soil and the leveelike structure in between Ramsgeul and Ramsdiep that needed work (see appendix G). These were specific requirements for Ramspol and do not hold for the Hartel location. For that reason it is expected that the costs for the Hartel location are 10% of the costs for the Ramspol location.

Ramspol			**Inflatable Hartel**		
Total costs Ramspol	5.200.000	€	Total costs Hartel	500.000	€

Table 6.8: Groundwork costs Ramspol and new Hartel barrier (1997 price level)

6.2.2. REMAINING GROUPS

For the following two groups has been determined that they are a percentage of the combined costs of the main groups, these are given in table 6.1. The total costs of the main groups are for both barriers are:

[5] See appendix H
[6] These will be the costs that will be used for the inflatable Hartel barrier

Ramspol			Inflatable Hartel		
Total costs main groups	27.500.000	€	Total costs main groups	21.700.000	€

Table 6.9: Total main group costs Ramspol and new Hartel barrier (1997 price level)

RISK, PROFIT AND UNFORESEEN

For risk, profit and unforeseen is found that they are about 31 % of the costs of the main groups and 18 % of the total costs of the barrier. This results in:

Ramspol			Inflatable Hartel		
Total costs Ramspol	8.500.000	€	Total costs Ramspol	6.700.000	€
Percentage of total costs	18%		Percentage of total costs	18%	
Percentage of costs main groups	31%		Percentage of costs main groups	31%	

Table 6.10: Risk, profit and unforeseen Ramspol and new Hartel barrier (1997 price level)

OTHER

These costs are also a very significant part of the total costs of the Ramspol barrier. They are about 44 % of the costs of the main groups and 25 % of the total construction costs, giving:

Ramspol			Inflatable Hartel		
Total costs Ramspol	12.100.000	€	Total costs Ramspol	9.500.000	€
Percentage of total costs	25%		Percentage of total costs	25%	
Percentage of costs main groups	44%		Percentage of costs main groups	44%	

Table 6.11: Other costs for Ramspol and new Hartel barrier (1997 price level)

6.3. CONSTRUCTION COSTS FOR RAMSPOL AND INFLATABLE HARTEL BARRIER

This section summarises the construction costs for the barrier. And when that is done, the costs are transformed to the 2014 price level.

6.3.1. CONSTRUCTION COSTS 1997 PRICE LEVEL

Table 6.12 shows the construction costs (1997 price level) per group and in total for both the Ramspol and the inflatable Hartel barrier.

	Ramspol		Inflatable Hartel	
Membrane	€10.600.000	22%	€7.700.000	20%
Abutments	€4.500.000	9%	€3.600.000	9%
Foundation	€2.400.000	5%	€1.500.000	4%
Bed protection	€1.400.000	3%	€6.000.000	16%
Installations	€3.400.000	7%	€2.800.000	7%
Groundwork	€5.200.000	11%	€500.000	2%
Risk, profit, unforeseen	€8.500.000	18%	€6.700.000	17%
Other	€12.100.000	25%	€9.500.000	25%
Total sum	**€48.100.000**		**€38.400.000**	

Table 6.12: Construction costs Ramspol and inflatable Hartel barriers (1997 price level)

6.3.2. CONSTRUCTION COSTS 2014 PRICE LEVEL

To end up with figures that are more relevant, the price level has to be adjusted to the current price level. This is done by using a well known equation that transforms real costs to nominal costs:

$$q_{n,d} = (1+d)^n \tag{6.2}$$

With $q_{n,d}$ is the inflation/deflation factor, d is the expected increase in prices per annum (the discount rate) and n is the number of years between base date end year of occurrence. The number of years in this case is 17 to go from 1997 to 2014. The discount rate for future costs that is used during this thesis is 2,5 %, see section 2.4 for more information about the discount rate[7]. Since the Ramspol barrier is still the only inflatable barrier until now it is assumed that the techniques have not improved or only very little. The results are given in table 6.13.

	Ramspol		Inflatable Hartel	
Membrane	€16.100.000	22%	€11.700.000	20%
Abutments	€6.800.000	9%	€5.500.000	9%
Foundation	€3.700.000	5%	€2.300.000	4%
Bed protection	€2.100.000	3%	€9.100.000	16%
Installations	€5.200.000	7%	€4.300.000	7%
Groundwork	€7.900.000	11%	€800.000	2%
Risk, profit, unforeseen	€12.900.000	18%	€10.200.000	17%
Other	€12.100.000	25%	€14.500.000	25%
Total sum	**€73.200.000**		**€58.300.000**	

Table 6.13: Construction costs Ramspol and inflatable Hartel barriers (2014 price level), based on an annual discount rate of 2,5 % and 17 years

[7]According to DataMarket (2012); Federal Reserve Bank of St. Louis (FRED) (2014) the interest rate during the period 1999 to 2012 was about 4% on average. This could also have been used as a discount rate to calculate the costs at the current price level. During this thesis a constant discount rate of 2,5% is used.

6.4. CONSTRUCTION COSTS HARTEL BARRIER

Ministerie van Verkeer en Waterstaat (2006) states that the construction costs for the original Hartel barrier were about 90 million guilders and construction finished in 1996. Table 6.14 gives the construction costs for the original Hartel barrier based on this information.

Construction costs		
Construction costs (1996 price level)	90.000.000	guilders
Construction costs (1996 price level)	40.800.000	€
Construction costs (2014 price level)	63.700.000	€

Table 6.14: Construction costs original Hartel barrier, based on a discount rate of 2,5 % and 18 years (Ministerie van Verkeer en Waterstaat, 2006)

It can be seen from this table, compared to table 6.13, that the construction costs for the inflatable Hartel barrier are expected to be slightly (about €5 million) lower than the construction costs for the original Hartel barrier.

It is very important to note that the construction costs for the inflatable Hartel barrier *include* the groups "Risk, profit and unforeseen" and "Other". It is unknown if and if so, to what extent these costs are included for the Hartel barrier. This could increase the difference in construction costs.

7

MAINTENANCE STRATEGIES AND COSTS AND DETERMINISTIC PV

An important part of the LCC is determined by the costs during the life of an asset. Within this chapter maintenance strategies will be discussed. By making use of a decomposition method the maintenance costs for the barrier have been approximated. The influence of the discount rate and lifetime of the membrane is investigated. Finally the deterministic values for the PV and EAC are presented.

7.1. FAILURE

The failure probability of an asset is a function of the resistance (R) of the asset and the load (S) on the asset. At the moment the load is bigger than the strength (S > R) the asset fails. The resistance and loads are not static numbers, but they are probabilistic distributions with a mean and a standard deviation (see figure 7.1). Furthermore, constructed assets usually loose strength during their lifetime due to deterioration processes (figure 7.2).

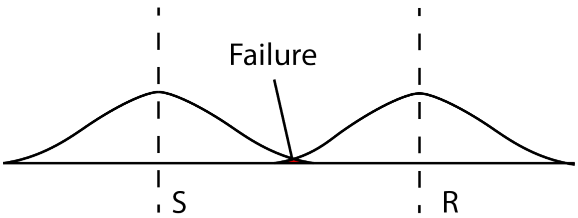

Figure 7.1: Failure of an asset if S > R

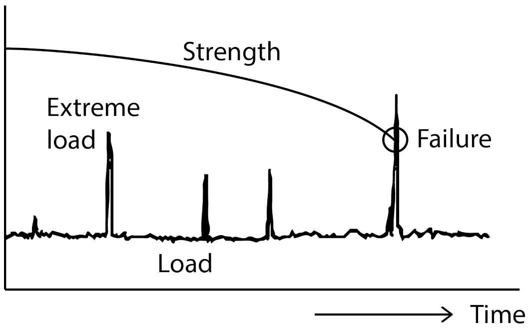

Figure 7.2: Strength of an asset decreases over time, failure of S > R

From figure 7.1 can be concluded that an asset with the same mean strength R but a smaller standard deviation will have a significantly smaller failure probability because its distribution will be narrower (see figure 7.3).

7.2. MAINTENANCE STRATEGIES

According to prof. drs. ir. J. K. Vrijling et al. (2002) and Schiereck (2012) one of the ways to minimise costs of an asset during its active life is to have a good maintenance strategy. Two main strategies can be distinguished:

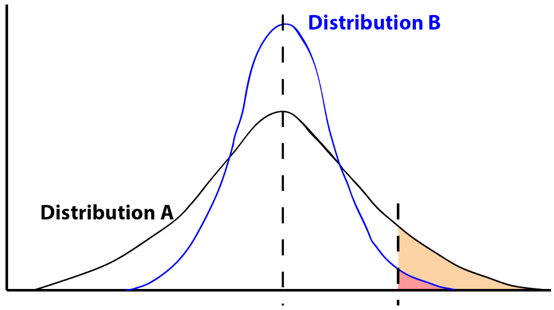

Figure 7.3: Smaller failure probability for smaller standard deviation. In orange the failure probability for distribution A > in red the failure probability for distribution B

1. Curative maintenance:
   An asset is only repaired or replaced if the asset is not longer able to fulfil its function.

2. Preventive maintenance:
   Maintenance or replacements take place at predefined moments or at predefined states of parts to ensure that the asset can fulfil its purpose.

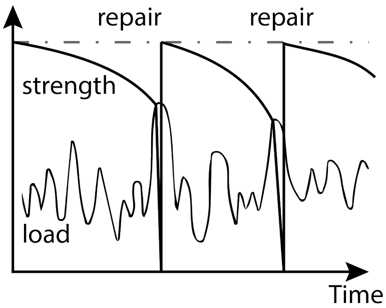

Figure 7.4: Failure based maintenance (based on Schiereck (2012))

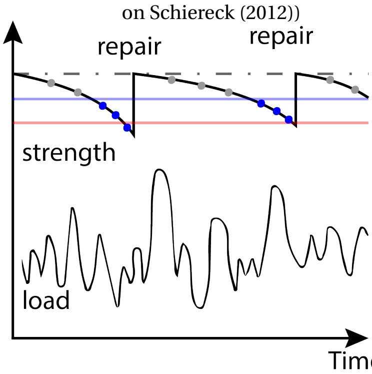

Figure 7.5: State based maintenance. Grey dots represent rough inspections, blue dots detailed inspections. The blue line is a warning limit and the red line is an action limit (based on Schiereck (2012))

Curative (or **failure based**) **maintenance** is shown in figure 7.4. The asset is repaired after failure, no work is done before failure. An advantage is that the full lifespan of an asset is used. A good example is a light bulb in for example a living room.

For preventive maintenance multiple strategies are available:

Figure 7.5 shows **state based maintenance**. This is probably the most common maintenance policy for hydraulic engineering purposes. The course of the strength of the structure must be predictable to some amount. The asset is checked roughly at fixed intervals, when the strength is lower than a warning limit detailed inspections will take place at shorter intervals. Action takes place when its found that the state of the asset is less good than a certain action limit.

Time based, use based and load based maintenance are given in figure 7.6. **Time based maintenance** means that maintenance takes place after a certain, predetermined, time. The requirement for this is that the deterioration rate can be predicted pretty good. **Use based maintenance** is a strategy based on the usage of the asset. Deterioration mainly takes place during usage. The last strategy, **load based maintenance**, can be used if deterioration rates are mainly influenced by loads. Cumulative or extreme loads determine if maintenance is required.

A method to determine which maintenance strategy is preferable for an asset is given by figure 7.7. However, often it is better to use a combination of strategies in stead of just relying on one of them. On basis of a combination of the time dependent, load dependent and state dependent strategy it can be decided to repair or replace (part of) the asset.

Because of the large consequences of failure of a storm surge barrier during extreme water levels a failure based maintenance strategy is inadvisable and will not be used for the designed barrier. The following sections will discuss the maintenance strategies per part of the structure.

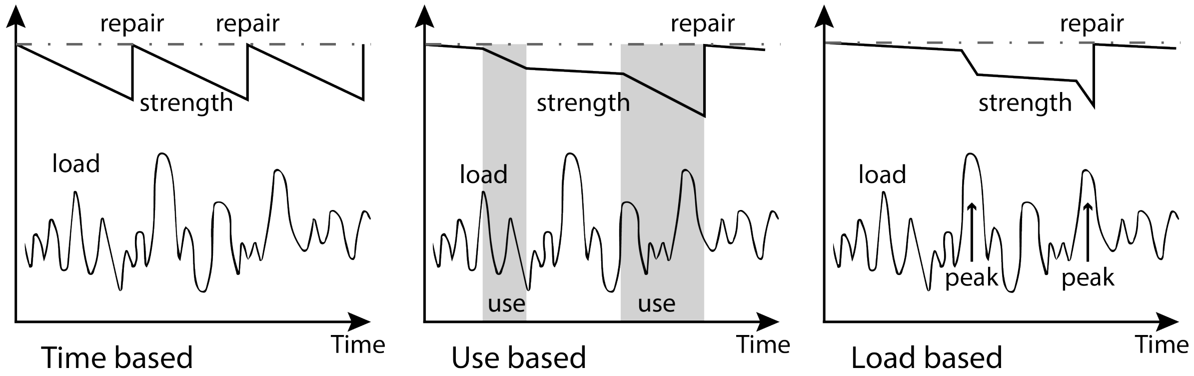

Figure 7.6: From left to right: time based, use based and load based maintenance strategies (based on Schiereck (2012))

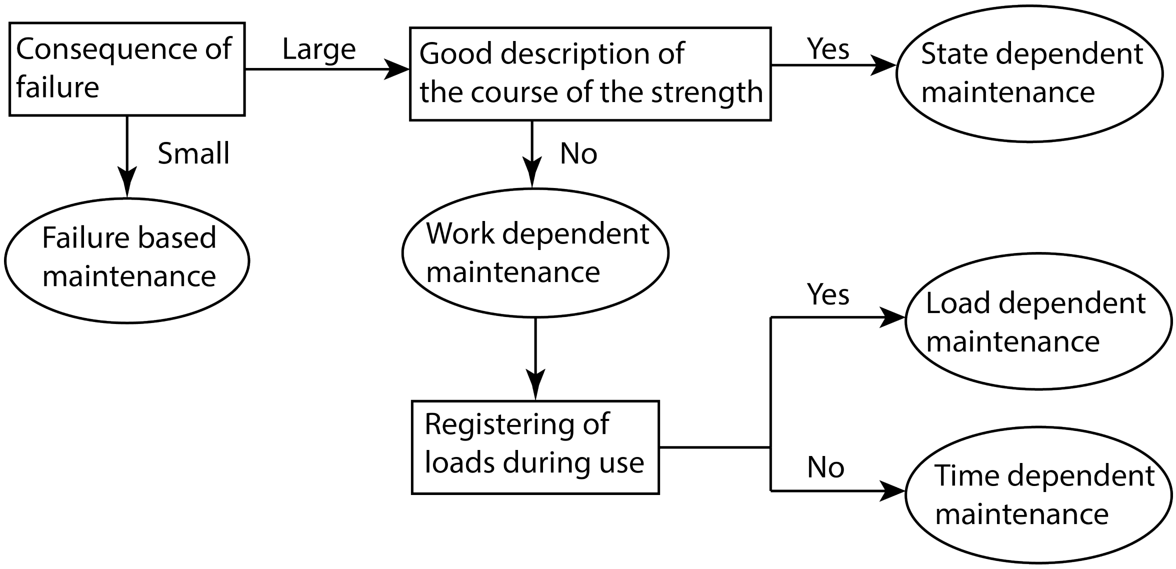

Figure 7.7: Choice for a maintenance policy (based on prof. drs. ir. J. K. Vrijling et al. (2002))

7.2.1. COMBINING MAINTENANCE OPERATIONS

The above shown maintenance strategies work for an asset in total or for parts of an asset individually. However, it could be beneficial to bring maintenance forward if it can be combined with another maintenance project. In that way the costs may be lower and/or safety may be higher. This is not included within this thesis but should be considered before every large maintenance operation. A separate LCC analysis can be useful to help with decision making. This may also have other benefits since new products may have new features. For instance maintaining the operating system at the same moment as the control system may give the operators more options since they can be designed to work together.

Also the maintenance of surrounding assets should be included in choosing a maintenance strategy. It can be beneficial to perform, for instance, maintenance on the abutments at the same time as doing maintenance at the adjacent levees.

7.2.2. PERIOD OF ANALYSIS

The period of analysis is chosen to be the standard required economical lifetime of 100 years for primary storm surge barriers in the Netherlands (*Beleidsnota Waterkeringen*, 2010). When an asset is near the end of its expected or required lifetime it could off course be that the asset is still in good shape. Another option is that the asset could deteriorate faster than expected and the lifetime is shorter. This is not included in this thesis but should be monitored during the life of the asset.

7.3. MANAGEMENT COSTS

For the management costs it is assumed that they are similar for both barriers and for that reason they don't have to be taken into account because they will not result in a difference. However, it is very important to note that management costs are in fact additional costs and, depending on the kind of analysis or information needed, could be taken into account. This would, obviously, result in a higher cost level.

7.4. DECOMPOSITION AND MAINTENANCE STRATEGIES

Within this section the decomposition of the barriers to a strategic level and the maintenance strategy per part will be discussed.

7.4.1. RAMSPOL

For Ramspol the following decomposition has been made (also see table 7.1), the costs are a best guess based on several sources:

- Membrane:
  The membrane is essential for the barrier as it is the water retaining part. The strength is monitored by pieces of the same material in the water so a state based maintenance regime is preferable. Of course a replacement will also take place if failure for some reason (e.g. a ship collision) occurs. For now, it is assumed that the membrane has to be replaced every 37,5 years (also see section 7.6). Yearly maintenance is not applicable. The base costs for replacing the membrane follow from table 6.13.

- Control system:
  The control system controls the barrier and gives the opening or closing commands (it is the ICT). Time based maintenance is usually the best strategy. Not only deterioration, but also new techniques are important aspects for replacing the control system. The costs are expected to be €1,5 to €2 million per 15 years. which gives €1,75 million per 15 years for deterministic purposes.

- Operating system:
  For the operating system holds that it opens and closes the barrier (the mechanical parts). The operating system is as important as the membrane. Because of the many parts of the system the exact state is less good to determine. However, the load can be determined quite exact. For that reason a load based conservation plan is chosen. The total construction costs for installations (CS and OS) are €5,2 million. The control system is included in these installations, which leaves €3,5 million for the operating system.

- Abutments:
  It is assumed that the abutments are designed for the same requirements as the foundation with a required lifetime of 100 years. However, because they are subjected to the flow of water, influence of the weather and the possibility of a collision the state must be monitored and it can be required to repair the abutments. The maintenance costs are expected to be 15 % of the construction costs.

- Guidance works ships:
  For the guidance works for ships a combination of load based and time based maintenance is used because both the deterioration and the ships colliding to the guidance works are important factors. The costs follow from table 6.13 and the lifetime should be 25 years.

- Offices:
  For the offices a combination of time and failure based maintenance is selected. Most of the interior can be treated as non essential and for that reason failure is allowable. To ensure safe work places, the offices themselves should be maintained regularly on a time basis. The costs are based on the construction costs and are expected to be €0,6 million per 50 years.

- Foundation:
  The foundation includes the storage system of the membrane. To make sure the membrane is not damaged during the inactive state of the barrier the membrane is stored. Because of a failure in the storage system the membrane has been damaged in the past. To ensure that the required safety conditions are met and to prevent high unexpected costs, failure is not allowed. Furthermore, checking the state is difficult because of the under water location. For that reason a time based maintenance strategy is chosen. Based on the construction costs the maintenance is assumed to be €0,25 million per 20 years.

- Bed protection:
  If the bed protection is designed correctly, a sudden failure is not expected. So checking the state of the bed protection after heavy conditions have occurred should be sufficient. This means a state based strategy. The maintenance costs are expected to be 10 % of the construction costs per 20 years.

- Groundwork:
  The waterway is split into two parts by a earthen body into a main stream of about 160 m (Ramsgeul) and a shipping canal of about 80 m (Ramsdiep). This body should be treated in the same way as the bed protection. The maintenance costs are expected to be 10 % of the construction costs.

Part		**Activity**		**Conservation plan**
	Action	Time scale	Costs per action	
Construction	Build	-	€73.200.000	
Membrane	Replace	37,5 years	€16.100.000	State based
Control system	Replace	15 years	€1.750.000	Time based
OS	Replace	25 years	€3.500.000	Load based
Abutments	Maintain	20 years	€1.000.000	State based
Guidance ships	Replace	25 years	€1.500.000	Load based/Time base
Offices	Repair	50 years	€600.000	Time based/Failure based
Foundation	Maintain	20 years	€250.000	Time based
Bed protection	Maintain	20 years	€200.000	State based
Groundwork	Maintain	20 years	€800.000	State based

Table 7.1: Construction and maintenance costs Ramspol barrier (with a membrane lifetime of 37,5 years) (2014 price level)[1]

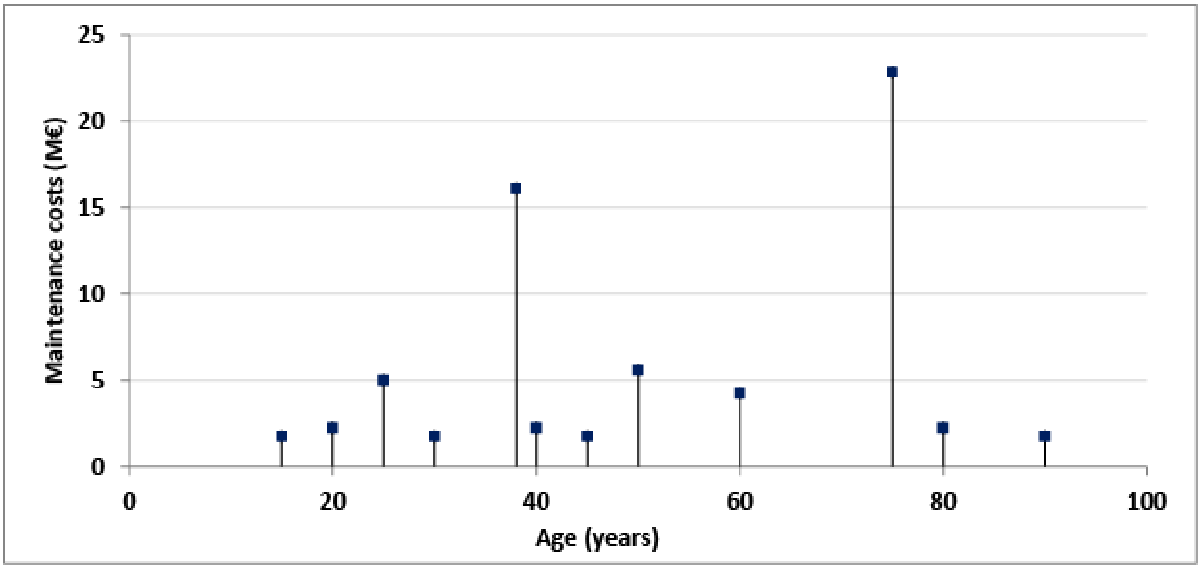

Figure 7.8: Maintenance costs for the Ramspol barrier. These costs are not discounted and are to illustrate when costs occur and show the occurrence of cost drivers

[1] Best guess based on several sources

7.4.2. INFLATABLE HARTEL

For the inflatable Hartel barrier holds that the maintenance strategies and costs for all parts except for the CS are based on the Ramspol decomposition. For the CS holds that it is assumed that the same control system will be used as is used for the Hartel barrier.

Part	**Activity**			**Conservation plan**
	Action	Time scale	Costs per action	
Construction	Build	-	€58.400.000	
Membrane	Replace	37,5 years	€11.700.000	State based
Control system	Replace	4 years	€1.250.000	Time based
OS	Replace	25 years	€3.000.000	Load based
Abutments	Maintain	20 years	€850.000	State based
Guidance ships	Replace	25 years	€1.500.000	Load based/Time base
Offices	Repair	50 years	€600.000	Time based/Failure based
Foundation	Maintain	20 years	€250.000	Time based
Bed protection	Maintain	20 years	€900.000	State based
Groundwork	Maintain	20 years	€100.000	State based

Table 7.2: Construction and maintenance costs inflatable Hartel barrier (with a membrane lifetime of 37,5 years) (2014 price level)[2]

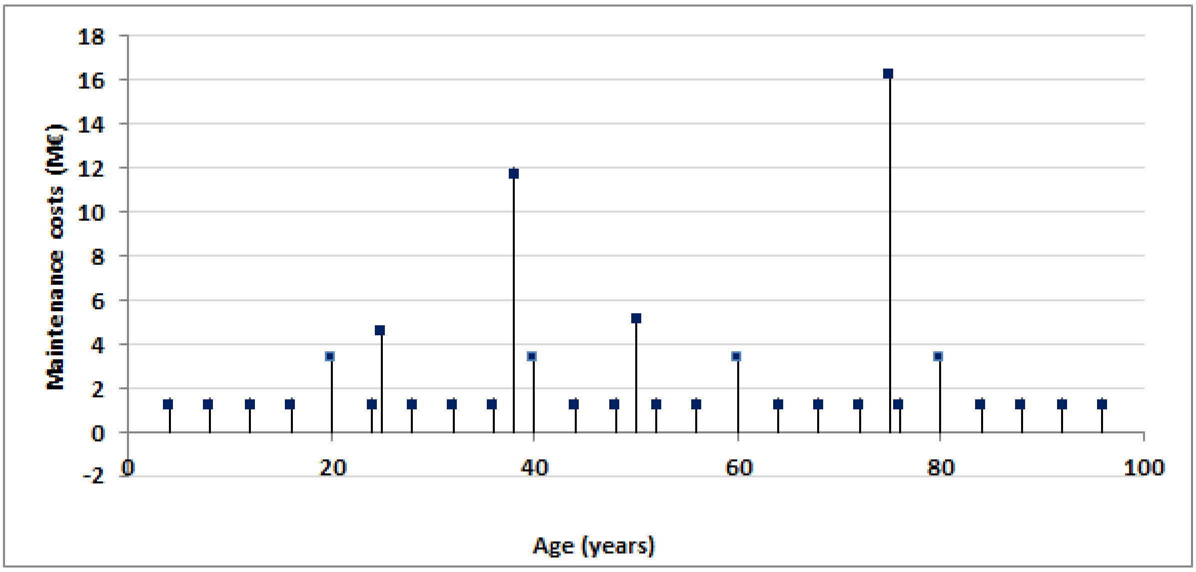

Figure 7.9: Maintenance costs for the Ramspol barrier. These costs are not discounted and are to illustrate when costs occur and the occurrence of cost drivers

[2]Based on Hartel and Ramspol costs and several sources

7.4.3. HARTEL

- Doors:
  The doors can get damaged and corrode over time. For that reason conservation works must be conducted. To ensure the safety level a time based strategy is used as main strategy. The deterioration rates can be predicted very good and for that reason a time based strategy is a good choice. However, because of the importance of the part also state based maintenance should be included. If corrosion or damage is detected, maintenance should take place.

  It is expected that the paint can last about 20 years. The costs for redoing the top layer of paint for the doors of the Hartel barrier are expected to be €3,5 million per event. The costs are estimated to be €15 million per event if the doors have to be stripped of all layers and have to be redone totally. This is based on best guesses and costs available from the Eastern Scheldt barrier. According to Minister J. R. H. Maij-Weggen (1994) conserving 30 doors for the Eastern Scheldt barrier in 1994 was estimated to cost 65 million guilders. This is about 6.000 guilder per square meter closure. According to Van der Laken (1999) the costs for conserving 2 doors appeared to be 4 million guilder per door and took 2 to 3 months. This is approximately 11.000 guilder per square meter (in 1994)[3]. The doors of the Hartel barrier close off a total of about 1370 m^2. With a unit price of 11.000 guilder/m^2 (if a mean door height of 8.8 m is used) this gives a total of about 15 million guilder in 1994. Converted to 2014 Euro this means: €15 million for conserving both doors.

  It is expected that stripping and redoing the entire paint job is required once every two times which would mean it would have to be done two times. However, redoing the entire paint in the 80th year of life would be unnecessary, since the barrier has to be operational for just 20 more years. For that reason it has been assumed that full repainting is not required but redoing just the top layer is also insufficient. An average cost level of €9,5 million has been used for the last maintenance event for the doors. All of this combined results in an average of €8 million per 20 years.

- Control system:
  See section 7.4.1 for the maintenance strategy. The control system for the Hartel barrier is combined with the control system for the Maeslant barrier. For these barriers hold that the closing strategy is dependent on both river discharges from inland and storm expectations from sea. For that reason a more advanced system is used. For this reason the replacement time and maintenance costs differ significantly from the Ramspol system. The costs are estimated to be about €1 million per year and €1 million per four years, which makes an averaged €1,25 million per four years.

- Operating system:
  The machinery that lifts and lowers the doors is very important for the barrier to work. A combination of load and time based strategies has been chosen to maintain it. The loads can be registered and if a certain (cumulative) value has been reached maintenance should take place. To be sure, maintenance should also take place after a certain period, even if the threshold loading has not been reached yet. The machinery can be overhauled or replaced. The costs are estimated to be €4 million per 15 years. This lifetime is used since it is usually the time the operating system is supported by the supplier and spare parts can be delivered. This is important for the availability of the asset; if the operating system is damaged it is required to be repaired within a certain amount of time.

- Abutments:
  See section 7.4.1. The costs are expected to be significantly higher since the abutments have to transfer all forces from the doors to the foundation. Based on this fact and the information given by table 7.4 the maintenance costs are estimated to be €3 million per 20 years.

- Mooring dolphins:
  The mooring dolphins are not essential for the barrier to work and can be replaced if they fail. To ensure a longer life, yearly conservation maintenance can be included. Since they are just the mooring

[3] Note: these are unit costs per square meter of water retaining area and not per square meter or area that has to be painted. This is also dependent on the shape of the profiles; I or H profiles have larger area that has to be painted than circular shapes. However, these costs appeared to match well with found numbers during interviews.

dolphins, one third of the costs of the guidance works for the Ramspol barrier has been used which is €0,5 million per 25 years.

- Offices:
  See section 7.4.1. The costs are estimated to be the same for both barriers.

- Foundation:
  The foundation and sill should be checked from time to time. State based maintenance is a good method to maintain them since the deterioration can be predicted pretty good and maintaining them is difficult because of its under water location. These costs are assumed to be twice as high as for the Ramspol barrier since forces are transferred via the abutments to the foundations which is more difficult.

- Bed protection:
  See section 7.4.1. The maintenance costs are expected to be 10 % of the construction costs per 20 years.

- Groundwork:
  See section 7.4.1. The costs for groundwork are expected to be 10 % of the construction costs per 20 years. The construction costs are expected to be the same as for the inflatable Hartel barrier.

Part	**Activity**			**Conservation plan**
	Action	Time scale	Costs per action	
Construction	Build	-	€63.700.000	
Doors	Conserve	20 years	€8.000.000	Time based/state based
Control System	Replace	4 years	€1.250.000	Time based
OS	Replace	15 years	€4.000.000	Load based / time based
Abutments	Maintain	20 years	€3.000.000	State based
Mooring dolphins	Replace	25 years	€500.000	Failure based
Offices	Repair	50 years	€600.000	Failure based/time based
Foundation	Maintain	20 years	€500.000	Time based / state based
Bed protection	Maintain	20 years	€1.000.000	State based
Groundwork	Maintain	20 years	€100.000	State based

Table 7.3: Construction and maintenance costs Hartel barrier (2014 price level)[4]

[4]Best guess based on several sources

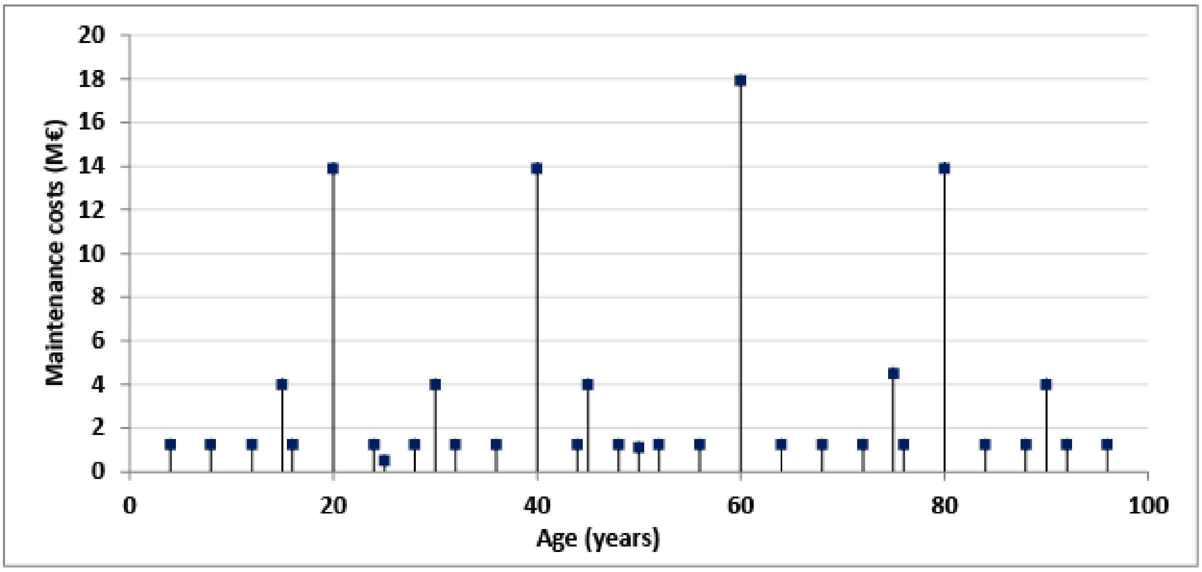

Figure 7.10: Maintenance costs for the Hartel barrier. These costs are not discounted and are to illustrate when costs occur the occurrence cost of drivers

ROUGH ESTIMATE MANAGEMENT AND MAINTENANCE COSTS HARTEL BARRIER

The management and maintenance costs for the Hartel barrier are given, as very rough indicates, by table 7.4. These costs also include management costs which are not included in this thesis. The management costs for Ramspol are estimated to be about €400.000 per year, as best guess this is also used for the Hartel barrier, which leaves €1.3 million per year for maintenance.

Barrier	Costs	Unit
Hartel en Maeslant	17.000.000	€/year
Maeslant (90% of total)	15.300.000	€/year
Hartel (10% of total)	1.700.000	€/year

Table 7.4: Yearly management and maintenance costs original Hartel and Maeslant barrier (2013 price level) (Rijkswaterstaat, 2014)

7.5. CUMULATIVE MAINTENANCE

Figure 7.11 shows the cumulative discounted maintenance costs for all three barriers. For this plot a discount rate of 2,5 % and expected membrane lifetime of 37,5 years is used. It can be seen that the maintenance costs for the Hartel barrier are the highest and the costs for Ramspol are expected to be the lowest. This can be a bit contra-intuitive since construction costs for the Rampol barrier are significantly higher. One of the reasons is the control system which has to be replaced every 4 years for the Hartel location and every 15 years for the Ramspol location. Another explanation can be found in figure 2.3: for higher construction costs a technically more advanced asset can be constructed, because of the more advanced technology the maintenance costs might be lower and this could result in lower LCC.

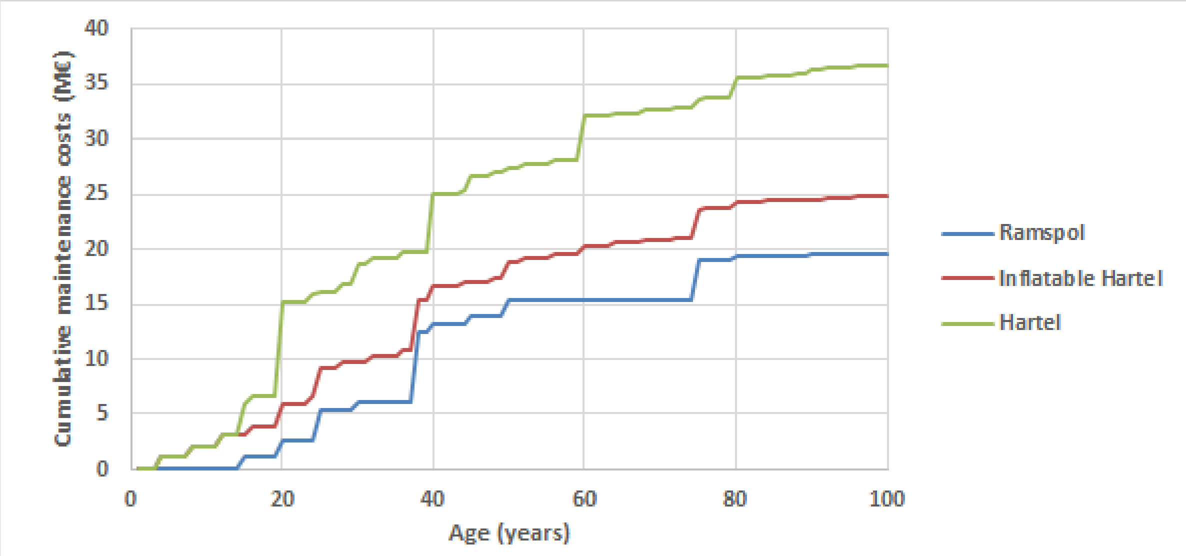

Figure 7.11: Discounted cumulative maintenance costs for the Ramspol, Hartel and inflatable Hartel barriers (with a membrane lifetime of 37,5 years)

From this figure can be seen that the graphs have some sort of basic steepness and some jumps. These jumps (or steps) can be explained as the maintenance operations on the doors or membrane (see the big bars in figures 7.8, 7.9 and 7.10). It can be seen that the steepness for the inflatable and original Hartel barrier are similar and the main difference is the number and height of the jumps. The difference between Ramspol and the inflatable Hartel barrier can be explained by the shorter lifetime of the CS for the Hartel location. The steepness for the Hartel location is greater and this results in higher LCC although the jumps are smaller.

7.5.1. INFLUENCE OF THE DIFFERENT COST GROUPS ON MAINTENANCE COSTS

Tables 7.5 and 7.6 show the total maintenance costs and the percentage of the total maintenance costs per group for the original and the inflatable Hartel barrier.

Cost group	PV maintenance	Relative to total
Groundwork	€130.000	1%
Bed protection	€1.210.000	5%
Foundation	€270.000	1%
Offices	€170.000	1%
Guidance ships	€1.480.000	6%
Abutments	€1.150.000	5%
OS	€2.960.000	12%
Control system	€10.920.000	44%
Membrane	€6.410.000	26%
Total	€24.800.000	

Table 7.5: Influence of cost groups on total maintenance PV for the inflatable Hartel barrier (deterministic, 2014 price level)

Cost group	PV maintenance	Relative to total
Groundwork	€130.000	0%[5]
Bed protection	€1.350.000	4%
Foundation	€670.000	2%
Offices	€170.000	0%[2]
Mooring dolphins	€490.000	1%
Abutments	€4.050.000	11%
OS	€7.960.000	22%
Control system	€10.920.000	30%
Doors	€10.790.000	30%
Total	€36.500.000	

Table 7.6: Influence of cost groups on total maintenance PV for the Hartel barrier (deterministic, 2014 price level)

7.6. LIFETIME MEMBRANE

The membrane lifetime is currently unknown. It is required to be at least 25 years, but the strength is monitored and the current expectancy is that it is more likely that the lifetime is going to be 50 years. For that reason figure 7.12 shows the cumulative maintenance costs for the inflatable Hartel barrier for three membrane lifetime scenarios: 25 years, 37,5 years and 50 years. It also shows the cumulative maintenance costs for the Hartel barrier. It can be seen that, regardless of the lifetime of the membrane, the cumulative maintenance costs for the inflatable Hartel barrier are lower than for the Hartel barrier. This is very useful information since the construction costs for the inflatable Hartel barrier are also lower.

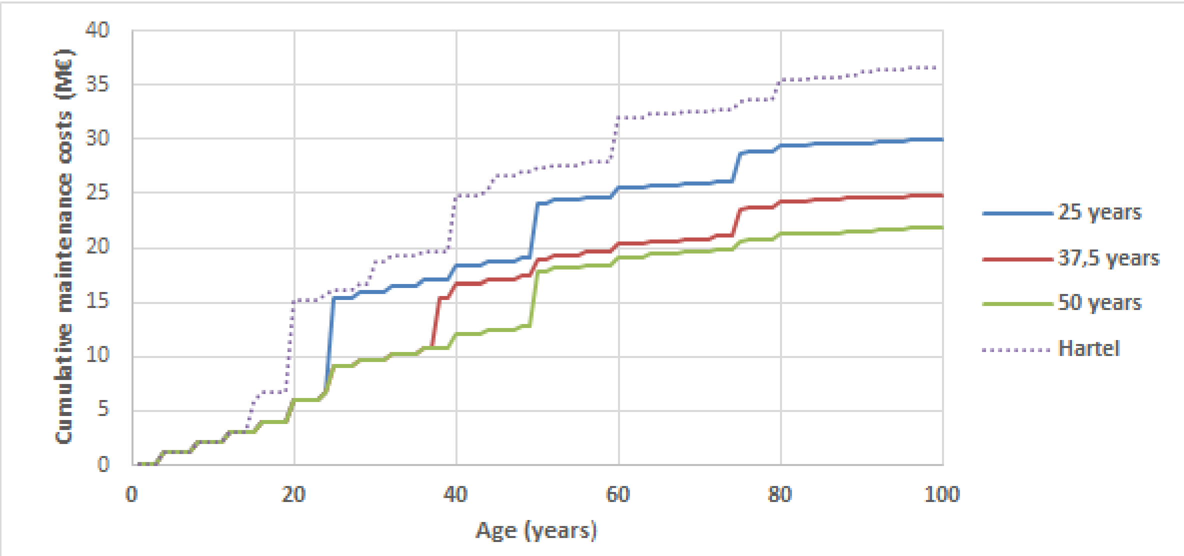

Figure 7.12: The influence of the lifetime of the membrane on the discounted maintenance costs

7.6.1. TEST DATA MEMBRANE STRENGTH

Figure 7.13 shows the results of the yearly tests on the membrane. There is no clear deterioration rate that can be extracted from this data, since there seems to be no deterioration. The low values for years 2004 and 2005 may be present due to a varying number of reinforcement fibres in the samples. Based on these samples

[5] The contribution is 0% due to rounding, actually it is of course a very small percentage less than 0,5 %

the lifetime of the barrier is expected to be a lot longer than 25 years. For that reason an expected lifetime of 37,5 years has been used throughout this research.

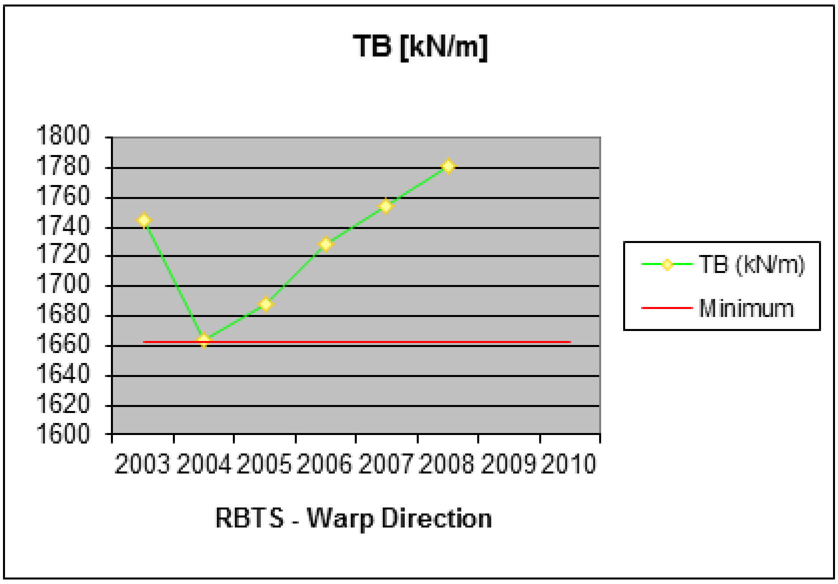

Figure 7.13: Test data for the membrane strength at Ramspol (provided by BAM)

7.7. DISCOUNT RATE

Costs that occur in the future should be reduced by a factor (discount factor) to take this into account. This factor is dependent on the discount rate. The discount factor can be calculated by:

$$q_d = \frac{1}{(1+d)^n} \tag{7.1}$$

With d is the discount rate and n is the number of years between the base date and the occurrence of the cost (ISO, 2008). A high discount rate will be favourable for assets with low construction costs, a short life and high recurring costs. A low discount rate will have an opposite effect (Kumar, Chattopadhyay, & Pannu, 2004). The lifetime of the assets in this thesis is the same for all alternatives, from this can be concluded that the alternative with the highest recurring costs and lowest construction costs will probably benefit the most from a high discount rate. Figure 7.14 illustrates the effect of varying discount rates for both the original- and the inflatable Hartel barrier.

Discount rate	Inflatable Hartel	Hartel
1,00%	€46.500.000	€66.400.000
1,75%	€33.400.000	€48.500.000
2,50%	€24.800.000	€36.500.000
3,25%	€18.900.000	€28.300.000
4,00%	€14.800.000	€22.500.000
4,75%	€11.800.000	€18.300.000

Table 7.7: PV of the maintenance costs for varying discount rates (2014 price level)

From table 7.7 can be seen that the net difference in maintenance costs becomes lower for increased discount rates. Furthermore maintenance for the original barrier becomes €48,2 million less costly and for the inflatable barrier just €32,6 million. However, relatively the inflatable Hartel barrier benefits more than the original one; at a discount rate of 1% the maintenance costs for the inflatable version are about 65% of the costs for the original one. For a discount rate of 4,75% this has decreased to 60%. From this can be concluded that the inflatable barrier benefits relatively more from a high discount rate than the original barrier.

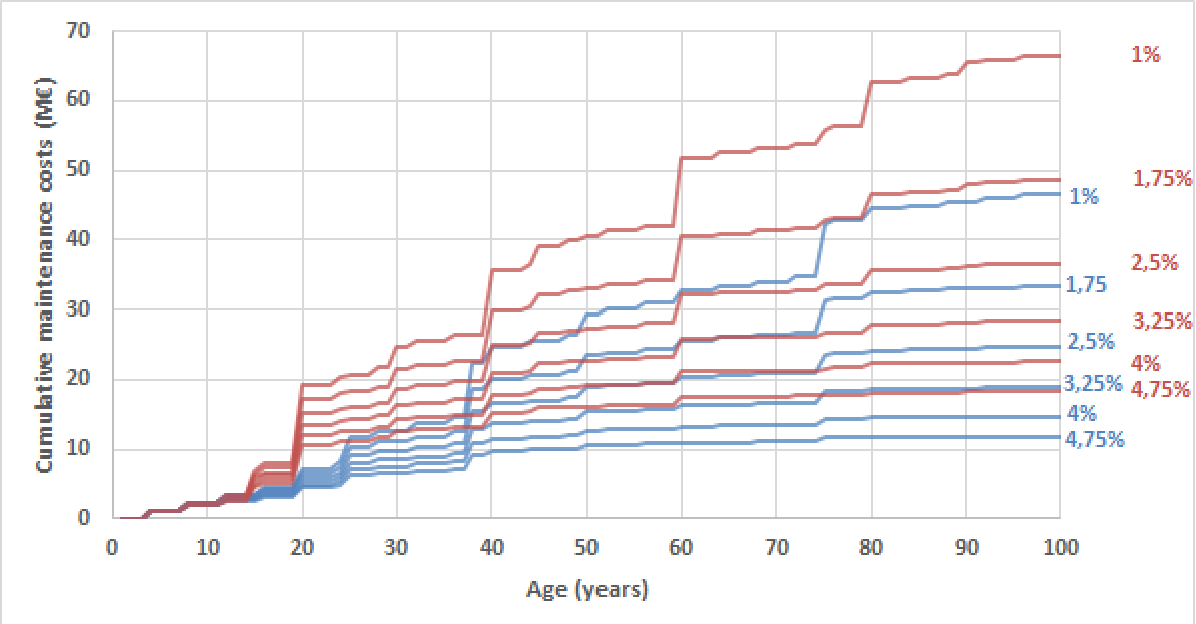

Figure 7.14: The influence of the discount rate on maintenance costs. The red lines and numbers represent the Hartel barrier, the blue ones the inflatable Hartel barrier. The percentages show the discount rate

Since it is very hard to predict if the discount rate will change and the influence on the outcomes is relatively low the discount rate will not be varied and is set to be a fixed 2,5%.

7.8. DETERMINISTIC VALUES FOR THE PRESENT VALUE OF THE LCC FOR THE BARRIERS

The total PV for the LCC of the barrier is given by table 7.8. For this thesis it consists of maintenance and construction costs. As can be seen from section 2.5 an LCC analysis may include more cost groups. For that reason these numbers may strictly be used for comparison/decision making purposes but cannot be used for budgeting.

Barrier	Construction	PV maintenance	Total PV
Ramspol	€73.200.000	€19.500.000	€92.700.000
Hartel	€63.700.000	€36.500.000	€100.200.000
Inflatable Hartel	€58.300.000	€24.800.000	€83.100.000

Table 7.8: Deterministic construction costs, PV of the maintenance costs and the PV of the LCC for all three barriers rounded at €100.000 (2014 price level)

From table 7.8 can be concluded that an inflatable barrier at the Hartel location could save about €20 million over the total life cycle.

7.8.1. THE DETERMINISTIC VALUE OF THE EAC OF THE LCC FOR THE BARRIERS

As already discussed in section 2.3 also the EAC can provide information about LCC. The EAC is mainly interesting for comparing assets with different lifetimes. It makes it possible to compare the annual costs and make a fair comparison. Since the lifetimes for both barriers are assumed to be the same (100 years) these EAC figures do not lead to a different conclusion. EAC can also be used for budgeting purposes and for that reason they are mentioned here.

	EAC maintenance	EAC LCC
Ramspol	€530.000	€2.530.000
Hartel	€1.000.000	€2.740.000
Inflatable Hartel	€680.000	€2.270.000

Table 7.9: Deterministic EAC for all three barriers rounded at €10.000 per year (2014 price level)

7.9. END-OF-LIFE COSTS

As has been suggested in section 2.5 demolition (or end-of-life) costs can be taken as percentage of the constructions costs. For bridges in Florida (USA) this appeared to be 30% to 35% for typical bridges. These costs have not been included in this thesis since no literature is available for end-of-life costs for storm surge barriers. Furthermore, taking them as a percentage of the construction costs will not result in other conclusions since the construction costs for the inflatable Hartel barrier are expected to be less than for the original barrier. Based on that, the end-of-life costs would also be bigger which would strengthen the conclusions drawn in this thesis.

8
Sensitivity Analysis

Within the following chapter the theory of a Monte Carlo simulation as tool for the sensitivity analysis will be discussed. In the following sections the input for the simulation and the results will be presented and explained.

8.1. Monte Carlo Simulation theory

For this thesis the Monte Carlo simulation has been used as a tool for the sensitivity analysis. This is a very powerful tool to sample a very large amount of results if the probabilistic parameters of the input are known. This is done by the generation of random, uniformly distributed numbers between one and zero. This function is usually provided for by most programming languages. The randomly generated numbers can be used as input for generating outcomes for one of the input parameters, no matter the distribution. This holds since the probability of non-exceedance is a uniformly distributed value between one and zero, regardless of the distribution of the parameter:

$$F_X(X) = X_u \tag{8.1}$$

with X_u is the randomly drawn number uniformly distributed between one and zero and $F_X(X)$ is the probability of non-exceedance. For every calculation a unique number must be used for every variable that has a distribution. This means that a very large number of random numbers has to be generated. The generation of variables is done by making use of the inverse distribution function of the variable:

$$X = F_X^{-1}(X_u) \tag{8.2}$$

with $F_X^{-1}(X_u)$ is the inverse probability density function of variable X (prof. drs. ir. J. K. Vrijling et al., 2002). If enough draws have been used the Central Limit Theorem can be used.

8.1.1. Central Limit Theorem

An important reason of performing a Monte Carlo Simulation is the Central Limit Theorem:

"*When a large number of independent random variables, of which none dominates, are added up, this results in a random variable that is normally distributed, irrespective of the starting distributions of the added variables*."[1]

This principle is used in this thesis to determine the cost levels with a 5% and 95% certainty of the costs per years.

[1] prof. drs. ir. J. K. Vrijling et al. (2002)

8.2. MONTE CARLO SIMULATION

Within this section the Monte Carlo Simulation, its input and the results will be discussed.

8.2.1. SIMULATION INPUT

The input for the Monte Carlo simulation can be found in tables 8.1 and 8.2. The background on the mean costs and lifetimes can be found in chapter 7. The standard variation values will be discussed here. All distributions have chosen to be normal.

Group	Costs (M€)		Time (years)	
	μ	σ	μ	σ
Construction	63,7	-	-	-
Doors	8	1,5	20	1,25
Control System	1,25	0,125	4	0,25
OS	4	0,0125	15	1
Abutments	3	-	20	-
Mooring dolphins	0,5	-	25	-
Offices	0,6	-	50	-
Foundation	0,5	-	20	-
Bedprotection	1	-	20	-
Groundwork	0,1	-	20	-
n[2]				10.000
Discount rate				2,5%

Table 8.1: Input Hartel for MC simulation

Group	Costs (M€)		Time (years)	
	μ	σ	μ	σ
Construction	58,4	-	-	-
Membrane	11,7	1,5	37,5	6,25
Control System	1,25	0,125	4	0,25
OS	3	0,25	25	1
Abutments	0,85	-	20	-
Guidance works	1,5	-	25	-
Offices	0,6	-	50	-
Foundation	0,25	-	20	-
Bedprotection	0,9	-	20	-
Groundwork	0,1	-	20	-
n[2]				10.000
Discount rate				2,5%

Table 8.2: Input inflatable Hartel for MC simulation

As can be seen most cost groups, including the construction costs, are taken constant. This is done to investigate only the governing parameters.

NON CONSTANT COST GROUPS

For the non constant cost groups both the costs as their expected lifetime have been chosen to be normally distributed. This is usually the approach if the actual distribution is unknown. For normal distributions hold the rules of thumb as shown in figure 8.1. This means that in 95% of the cases the value is within two standard deviations from the mean. Table 8.3 and 8.4 show the minimum and maximum values with a 95% certainty for the Hartel and inflatable Hartel barrier.

	Costs (M€)		Lifetime (years)	
	min	max	min	max
Doors	5	11	17,5	22,5
Control system	1	1,5	3,5	4,5
OS	3,5	4,5	13	17

Table 8.3: Min. and max. values for the Hartel barrier with a 95% certainty

	Costs (M€)		Lifetime (years)	
	min	max	min	max
Membrane	8,7	14,7	25	50
Control system	1	1,5	3,5	4,5
OS	2,5	3,5	23	27

Table 8.4: Min. and max. values for the inflatable Hartel barrier with a 95% certainty

These values have been chosen on the basis of available information and interviews.

[2]Number of draws

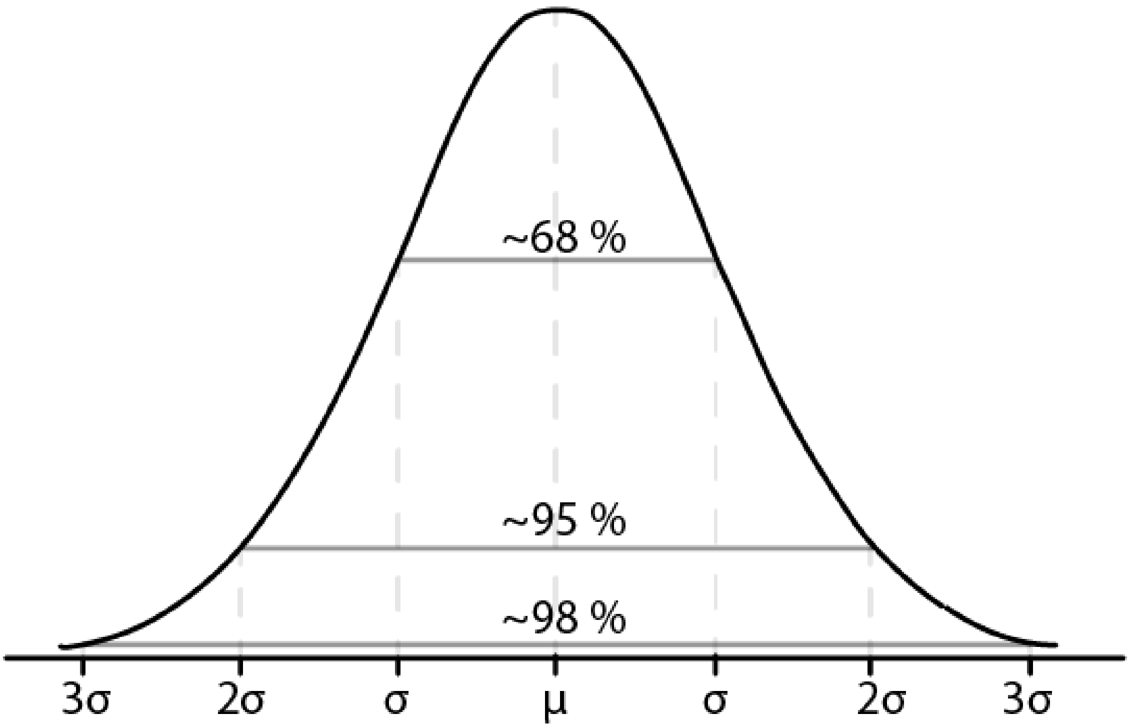

Figure 8.1: Bell curve belonging to normal distributions. About 68% of the data falls within one standard deviation of the mean, about 95% within two standard deviations and about 98% within three.

8.2.2. RESULTS HARTEL

The results of the Monte Carlo simulation are shown in figure 8.2. It illustrates the cumulative LCC for the Hartel barrier over its lifetime. Furthermore the cost levels with a 5% and 9% certainty are given, based on a normal distribution of these costs (Central Limit Theorem). The line belonging to 95 % represents the cost level that will be exceeded with a probability of 5 %. So in 95 % of the cases the costs will be lower or equal to this cost level. The 50 % line represents the mean value.

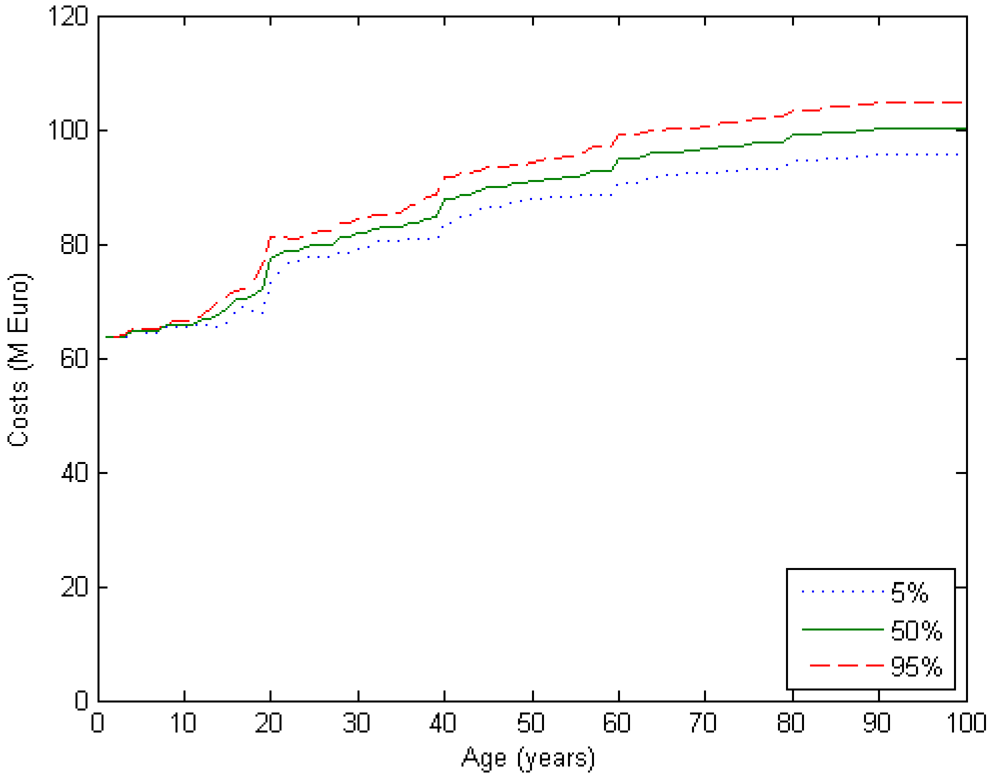

Figure 8.2: Total life cycle costs and probabilities of certainty for the Hartel barrier

Table 8.5 shows the mean and the standard deviation of the PV under the assumption that it is normally distributed. It can be seen that the mean from this MC simulation is almost similar to the deterministic total PV given in table 7.8.

	μ	σ
PV	€100.300.000	€2.790.000

Table 8.5: Mean and standard deviation of the PV for the Hartel barrier

8.2.3. RESULTS INFLATABLE HARTEL

Figure 8.3 gives the results for the inflatable Hartel barrierand table 8.6 gives the mean and standard deviation of the PV for this LCC.

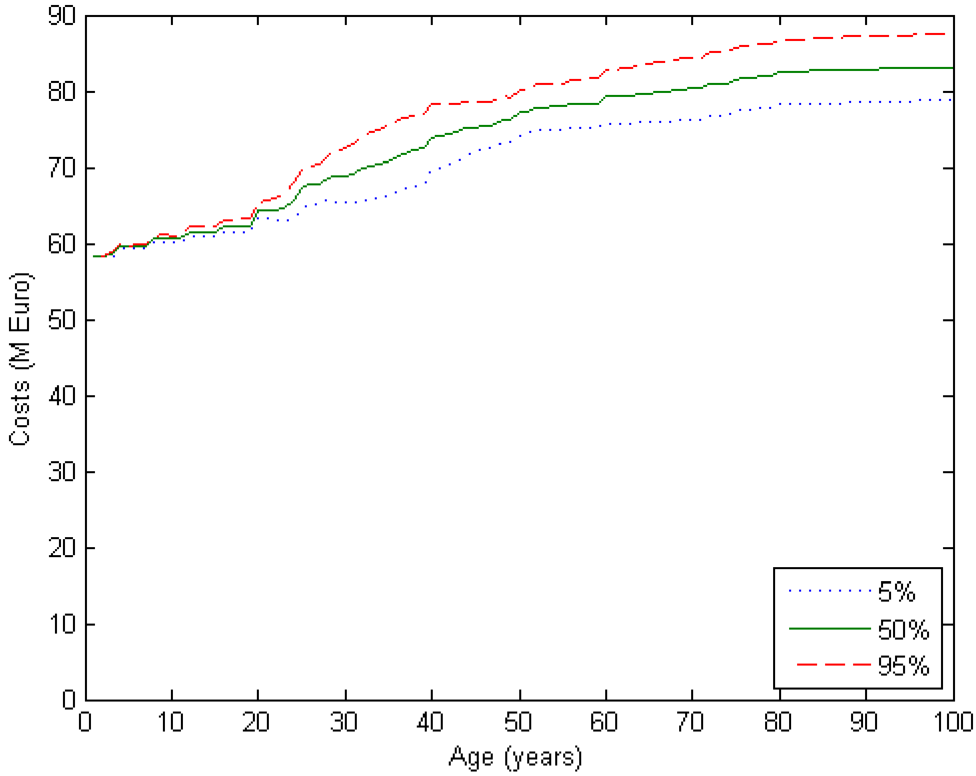

Figure 8.3: Total life cycle costs and probabilities of certainty for the inflatable Hartel barrier

	μ	σ
PV	€83.100.000	€2.670.000

Table 8.6: Mean and standard deviation of the PV for the inflatable Hartel barrier

8.2.4. PRESENT VALUE

Table 8.7 summarises the results for the sensitivity analysis and shows the 5% and 95% confidence intervals.

Barrier	Construction	PV maintenance (mean)	Total PV (mean)	PV (5%)	PV (95%)
Hartel	€63.700.000	€36.600.000	€100.300.000	€95.700.000	€104.900.000
Inflatable Hartel	€58.400.000	€24.700.000	€83.100.000	€78.700.000	€87.500.000

Table 8.7: Present Value for construction costs, maintenance costs and the total LCC and the 5% and 95% confidence levels (2014 price level)

8.2.5. EQUIVALENT ANNUAL COSTS

Table 8.8 provides the mean and standard deviation for the EAC for the maintenance costs and for the total LCC. These match with the values found in section 7.8.1. Both the mean values as the uncertainties are higher for the original barrier.

	EAC maintenance		EAC LCC	
	μ	σ	μ	σ
Hartel	€1.000.000	€80.000	€2.740.000	€80.000
Inflatable Hartel	€670.000	€73.000	€2.270.000	€73.000

Table 8.8: EAC LCC barriers of just maintenance and for the LCC

8.3. RESULTS AND STATISTICAL PARAMETERS

Other relevant statistical information is provided by the coefficient of variation, the skewness and the kurtosis of a dataset. Since the construction costs have been taken constant these parameters have been determined for the maintenance costs only. The skewness and kurtosis hold also for the total LCC, the coefficient of variation does not. The parameters will be discussed in the following sections. Appendix I provides more statistical information about the results.

COEFFICIENT OF VARIATION

The coefficient of variation is usually used as a measure of the dispersion of a probability function. It is a dimensionless coefficient and for that reason is particularly useful to compare datasets, even if the datasets have a very different mean.

$$V_X = \frac{\sigma_X}{\mu_X} \tag{8.3}$$

With V_X is the coefficient of variation. Equation (8.3) also shows why the coefficient of variation only holds for the total maintenance and not for the total LCC; if the construction costs are added μ_X significantly increases, but σ_X stays the same. This would give a very low value for the coefficient of variation.

SKEWNESS

The skewness is a measure for the asymmetry of a dataset. It can be calculated by:

$$\beta_1 = \frac{\mu_3}{\sigma^3} \tag{8.4}$$

With β_1 is the skewness. If $\beta_1 > 0$ the dataset has a positive skew and it means the right tail for the distribution is longer. If $\beta_1 < 0$ the opposite holds. The skewness is not affected by adding the construction costs.

KURTOSIS

The kurtosis is a measure for the peakedness of a probability density function. It can be calculated by:

$$\beta_2 = \frac{\mu_4}{\sigma^4} \tag{8.5}$$

With β_2 is the kurtosis. If $\beta_2 > 0$ the dataset has a positive kurtosis it is called leptokurtic. For leptokurtic distributions hold that they have a rather acute peak and fat tails. Distributions with a negative kurtosis are called platykurtic and they have a lower (and wider) peak and thin tails. The kurtosis is not affected by adding the construction costs.

STATISTICAL PARAMETERS

The statistical parameters for both the Hartel and inflatable Hartel barrier are given by table 8.9.

	Total maintenance costs				
	μ	σ	V_X	β_1	β_2
Hartel	€36.600.000	€2.790.000	0,076	0,29	3,58
Inflatable Hartel	€24.700.000	€2.670.000	0,108	0,76	4,73

Table 8.9: EAC LCC barriers of just maintenance and for the LCC

Both from figures I.1 and I.4 (in appendix I) and table 8.9 can be seen that the inflatable Hartel barrier has a higher kurtosis and skewness than the Hartel barrier.

8.3.1. SENSITIVITIES

The sensitivity of the outcome to changes in a certain parameter is also very useful information. The sensitivity of an outcome $Y(X)$ to changes in parameter X can be calculated by equation (8.6).

$$S_X^{Y(X)} = \left| \frac{\partial Y(X)}{\partial X_i} \right|_{X^0} \tag{8.6}$$

With in this case $S_X^{Y(X)}$ is the sensitivity of Y to changes in X, $Y(X)$ is the PV and X is the parameter that is changed. X^0 represents the mean value of that parameter.

A value of 0,10 for $S_X^{Y(X)}$ means that if X increases by 100%, $Y(X)$ increases by 10%. And if X increases by 10%, $Y(X)$ increases by 1%. Also negative values for the sensitivity are possible; for instance a value of -0,10 for $S_X^{Y(X)}$ means that if X increases by 100%, $Y(X)$ *decreases* by 10%.

COSTS

Tables 8.10 and 8.11 show the sensitivities of the PV of the maintenance costs to changes in the height of the costs for the different parts. Only the parts that are given a distribution, and thus are able to change, are considered.

Part	Sensitivity to costs
Doors	0,30
CS	0,30
OS	0,22

Table 8.10: Sensitivity of the PV of the maintenance costs to costs for the Hartel barrier

Part	Sensitivity to costs
Membrane	0,26
CS	0,44
OS	0,12

Table 8.11: Sensitivity of the PV of the maintenance costs to costs for the inflatable Hartel barrier

So for the Hartel barrier changes in the height of the costs of the conservation of the doors and the CS are slightly more influential, but no real big difference can be seen. For the inflatable Hartel barrier changes in costs for the CS are most relevant and changes in the costs of the OS are least relevant. Note: the values of the sensitivities are exactly the same as the percentage of the total maintenance costs each group is responsible for.

LIFETIMES

The sensitivity of the PV to the lifetime is less easy to determine since the costs are discounted[3] and because the number of times an item has to be replace changes. For the lifetimes hold that the sensitivities will be

[3] The year in which the costs occur determine the height of the costs since they are discounted. This is non-linear.

negative since an increase in lifetime causes a decrease in PV[4]. No clear relation has been found for the sensitivities to changes in lifetimes. Tables 8.12 and 8.13 show *order of magnitude* sensitivity values but it is very important to state that the sensitivity for lifetimes is not a fixed number.

Part	Sensitivity to costs
Doors	-0,40
CS	-0,30
OS	-0,25

Table 8.12: Sensitivity of the PV of the maintenance costs to lifetimes for the Hartel barrier (*order of magnitude*)

Part	Sensitivity to costs
Membrane	-0,55[5]
CS	-0,5
OS	-0,15

Table 8.13: Sensitivity of the PV of the maintenance costs to lifetimes for the inflatable Hartel barrier (*order of magnitude*)

8.3.2. INFLUENCE COEFFICIENTS

In order to be able to say something about the relative influence of the spread of the parameters on the spread of the PV this has been calculated by:

$$\alpha_X = \frac{\sigma_X}{\sigma_{Z(X)}} \tag{8.7}$$

In which σ_Z is the standard deviation of the final outcome, in this case the standard deviation for the PV, σ_X is the standard deviation of part X and α_X is the influence coefficient of parameter X. The higher an α-value, the larger its uncertainty and thus the higher the influence on the spread of the outcome. Tables 8.14 and 8.15 give the α-values for the doors, membrane, CS and OS. The standard deviations follow from the MC simulation, they represent the standard deviations over the total maintenance costs per part.

Part	σ_X (M€)	α
Doors	2,21	0,79
CS	1,31	0,47
OS	0,9	0,32
Z	2,79	-
Sum α^2		0,95

Table 8.14: Relative influence of coefficients for the Hartel barrier for the doors, CS and OS

Part	σ_X (M€)	α
Membrane	2,31	0,87
CS	1,28	0,48
OS	0,18	0,07
Z	2,67	-
Sum α^2		0,99

Table 8.15: Relative influence of coefficients for the inflatable Hartel barrier for the membrane, CS and OS

From these tables can be seen that for the inflatable Hartel barrier the membrane is by far the part with the highest uncertainty and for the Hartel barrier the doors have the highest uncertainty. Getting a better understanding of the lifetime and costs of the membrane and doors is the most effective way of improving the results of this analysis.

8.3.3. ANALYSIS OF THE RESULTS

Based on this simulation the same basic conclusions can be drawn as from section 7.8; the maintenance costs for the Hartel barrier are higher than of the inflatable edition. Furthermore, the original barrier has a higher uncertainty with regard to the maintenance costs and thus to the LCC. But the membrane of the inflatable Hartel barrier is the part with the highest uncertainty, getting more knowledge about the lifetime and replacement costs will improve the result the most.

The full Matlab code for the Monte Carlo simulation for the Hartel barrier can be found in appendix K.

[4]Discounting in a later year makes it less costly and a longer lifetime means less maintenance actions have to be performed.
[5]For this sensitivity values ranging from -0,91 to -0,34 have been found. This stresses again how important it is to use these numbers with great care and only to use them for order of magnitude calculations!

9
LCC COMPARISON IN GENERAL

This thesis is about an LCC comparison between inflatable storm surge barriers and traditional, vertical lifting door, storm surge barriers. In this light a case study for the Hartel location has been conducted. Since the thesis is about the general concepts this chapter will discuss some of the relevant aspects. The aspects that will be treated are:

- Costs for function loss
- Gate length
- Hydraulic head
- Water depth
- Ship collision
- Adaptability
- Inflatable barrier with no abutments
- Aesthetics

The goal is to investigate the sensitivities of inflatable and traditional barriers to changes in for instance water levels and the consequences of unwanted events like failure or ship collisions. Based on these analyses some general conclusions will be drawn. These are summarized in the end.

9.1. COSTS FOR FUNCTION LOSS

As already has been discussed in section 2.5, some theories suggest that LCC analyses should include costs for function loss. These costs should be included as yearly costs and should be calculated by multiplying the probability of function loss by the costs of the consequences of this loss of function in the year it occurs. This is a very open guideline and some questions come to mind when thinking this over:

- *What is the yearly probability of function loss for a storm surge barrier (or for the Hartel barrier)?*
  It is very hard to determine the yearly probability of function loss of a storm surge barrier. A full probabilistic analysis should be conducted to be able to determine this. Already several failure probabilities per event can be found; Van der Burgh, Lassing, and van de Paverd (1998) suggest a failure probability of 10^{-3} per event for the Hartel barrier, Bijl (2006) claims that it might have increased to 10^{-2} per event and also probabilities in the order of $5 \cdot 10^{-2}$ per event have been heard. If a proper failure probability per event is found this has to be translated to a failure probability per year.

- *How to include phenomena like sea level rise and climate change?*
  Intergovernmental Panel on Climate Change (IPCC) (2013) discusses the phenomena associated with climate change such as sea level rise. A sea level rise of 0,55 m to 1,25 m in 2100 relative to the sea level in 1700 is expected. Currently the sea level is already about 0,35 m higher than the sea level in 1700 which means an additional sea level rise of 0,2 m to 0,9 m the next 90 years could occur.

- *Should the yearly probability of function loss include deterioration and maintenance?*
  As already has been discussed in chapter 7, strength usually decreases over time which would mean that the probability of function loss should increase. Furthermore, maintenance works could (or should) lead to decreased probabilities of function loss.
- *How to determine the costs of the consequences?*
  It is difficult to determine what costs should be included in the costs for function loss; direct economical damage, loss of life, indirect economical damage, etc. Melisie (2006) used a method with direct consequences, direct consequences due to business failure and indirect consequences due to business failure. Jonkman (2007) worked on a general approach for loss of life estimations. However, both do not include failure for the Hartel barrier.
- *What are the costs of the consequences of function loss?*
  It is very difficult to determine the costs that should be associated with function loss for a storm surge barrier. According to Jonkman (2007) the economic damage for failure of the Maeslant barrier could be €11,3 billion. This could be used to estimate on the economic damage for the Hartel barrier since they protect the same region. However, this would be a very rough estimate.
- *How to include changing (increasing) costs of function loss?*
  In the future it is expected that the Netherlands and the world will be more densely populated. This increases probably the loss of life rates, but also the direct and indirect economical damage. Since the projected lifetime of a barrier is 100 years this could lead to a very relevant increase in consequences.

Answering all these questions (and probably more will come up during the process) is outside the scope of this thesis. However, since safety, failure and consequences are very important aspects this has been analysed qualitatively. Another reason for not including them is that including rough estimates for the costs of function loss would influence the rather good estimations for the construction and maintenance costs and make the results less reliable.

9.1.1. FAILURE MODES

Appendix J shows the event tree for a storm and/or rain event for a storm surge barrier at the Hartel location. This will probably be very similar at other locations. Most of this tree will be exactly similar for both the inflatable- and the traditional barrier. However, a different situation may occur at failure due to high loads (load > strength). It has been assumed that the control system and operating system have the same failure probability, so the probabilities that the expected water level is correct and that the barrier will close are similar for both barriers.

FAILURE HARTEL

For the original Hartel barrier holds that the doors are designed for a certain load. If the load is higher than the strength the doors may fail structurally. However, extra safety is provided by the material which will make the doors yield before they completely fail. This means that the doors cannot withstand the bending moment that is present due to the load and the doors may break. This is a very dangerous failure mechanism since failure of the doors means that the barrier is not able to fulfil its purpose.

FAILURE INFLATABLE HARTEL

For an inflatable barrier holds that if the loads get higher than the design load the barrier may be pushed down a bit allowing more overflow. However, the barrier would still retain part of the water. At a certain moment the tensile force in the membrane may become larger than the strength and the membrane may fail completely. It is uncertain if this really happens or if the bellow is just pushed down.

Figures 9.1 and 9.2 illustrate what this may look like. For both figures hold that only the right (longer) gate fails or partly fails. Note: the doors for the Hartel barrier could break but this is a very extreme failure mode. It is very well possible that the doors will yield and still retain part of the water.

9.1.2. EFFECT ON LCC

The effects on the LCC is split up into two parts: the effects for the case study and the effects in general.

[1] This illustration shows the most extreme situation with completely failed doors. The doors will first yield and may not even break at all.

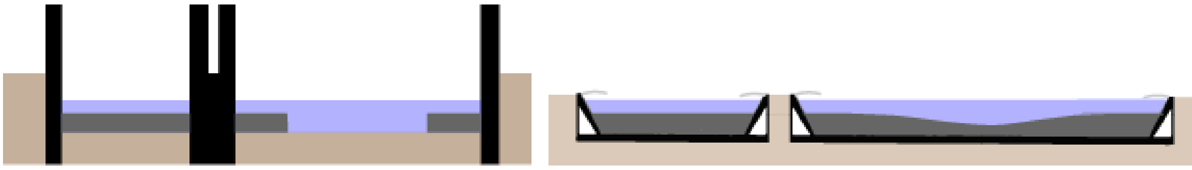

Figure 9.1: Example of what a failing barrier may look like (side view). Left a vertical lifting door barrier (Hartel) and right an inflatable barrier (inflatable Hartel)

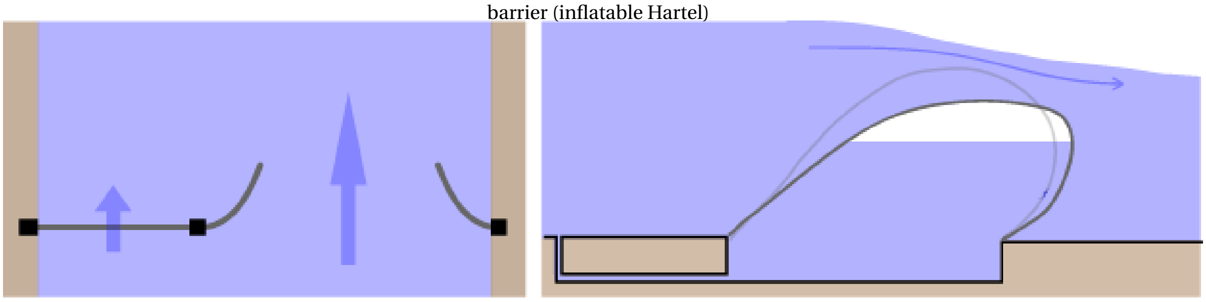

Figure 9.2: Example of what a failing barrier may look like (top view and cross section). Left a vertical lifting door barrier (Hartel) [1] (overflow is also shown) and right an inflatable barrier (inflatable Hartel), the original position of the membrane is also shown

CASE STUDY

In case of the Hartel location can be said that the failure mode for the inflatable Hartel barrier gives a higher safety level than the Hartel barrier does. Both barriers might eventually fail if the loads are too high for the material, but for the inflatable Hartel barrier the consequences might not be as devastating as for the Hartel barrier. This will result in lower costs for function loss and this will positively influence the LCC. Furthermore, the costs for repairs for the barrier will be lower for the inflatable barrier since no complete door has to be replaced. However, the remaining strength of the membrane should be checked. Also the impact and damage the abutments may be higher for the traditional barrier.

Since the failure modes for the inflatable barrier are largely unknown and the doors have some (hidden) extra strength it is very difficult to determine which barrier type has the least dangerous failure mode. The failure probability per event for Ramspol is also 3,5 times as high as for the Hartel barrier, during this qualitative analysis they are assumed to be equal. Based on this analysis it is impossible to determine which barrier has the lowest costs for function loss.

IN GENERAL

The conclusions for the case study also hold in general. If both barriers have the exact same failure probabilities, there are reasons to assume that failure of an inflatable barrier will be less devastating than for a vertical lifting door barrier. However, to many unsubstantiated assumptions have been made to draw conclusions.

9.2. VARYING GATE LENGTHS

If the opening that has to be closed becomes wider, longer gates may be beneficial. By doing this the amount of abutments decreases and the costs may also decrease. This has been investigated by calculating the influence of longer gates on the bending moments for doors and the tensile force in the membrane for inflatable barriers. The head and height of the gates have been kept constant. An outside water level of 10 m has been used and an inside water level of 7 m, resulting in a head of 3 m. The results can be seen in table 9.1 and figure 9.4. The model that has been used for the door is illustrated by figure 9.3. For the membrane the spreadsheet of Dirkmaat has been used. The maximum length is 150 m, as already stated Van Breukelen (2013) showed that bellows with a length of 210 m are feasible.

Length (m)	Max. moment		Tensile force	
50	78.173	kNm	346	kN
60	112.570	kNm	346	kN
70	153.220	kNm	346	kN
80	200.124	kNm	346	kN
90	253.282	kNm	346	kN
100	312.694	kNm	346	kN
110	378.359	kNm	346	kN
120	450.279	kNm	346	kN
130	528.452	kNm	346	kN
140	612.880	kNm	346	kN
150	703.561	kNm	346	kN

Table 9.1: Bending moments for doors versus tensile force in membrane by increasing gate length. In this case with a head of 3 m (outside 10m, inside 7m)

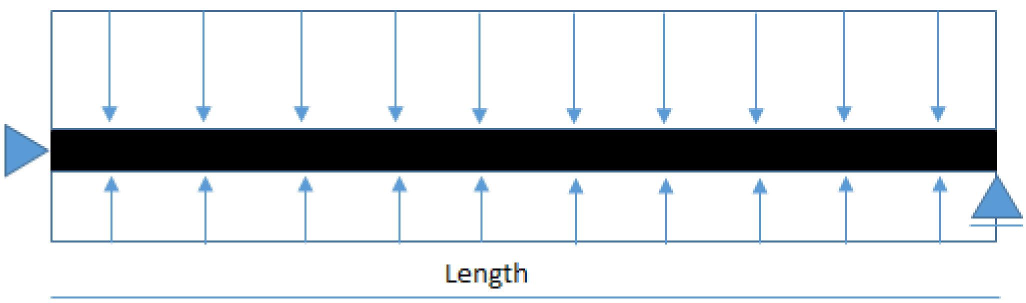

Figure 9.3: Model used for calculating the impact of longer beams for vertical lifting doors (top view)

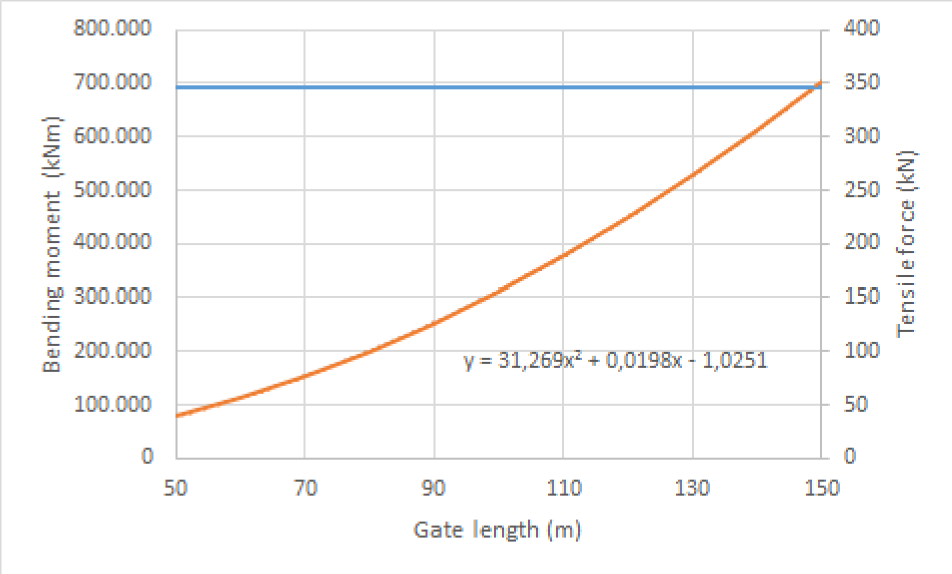

Figure 9.4: Bending moments for doors (orange) versus tensile force in membrane (blue) by increasing gate length. In this case with a head of 3 m (outside 10m, inside 7m)

9.2.1. Doors

The maximum bending moment can be calculated by making use of equation (9.1). The distributed load for the inside water level should be subtracted from the load for the outside water level and used in equation (9.1). However, these results are obtained by making use of MatrixFrame.

$$M = \frac{1}{8}ql^2 \tag{9.1}$$

According to Hartsuijker (2001) the extreme bending stresses are present at the outer fibres. For a symmetrical cross section these stresses can be calculated by equation (9.2).

$$\sigma = \frac{M}{W} \tag{9.2}$$

With M is the acting bending moment (kNm) and W is the resisting moment capacity (m^3). The resisting moment for a rectangle can be calculated with equation (9.3).

$$W = \frac{1}{6}bh^2 \tag{9.3}$$

If the door is modelled as a rectangle with b is the length of the barrier (m) and h is the thickness of the barrier (m) it follows that the bending moment will be related to the length of the door squared and the resisting moment will be related to the thickness of the door (see equation (9.4)).

$$\sigma = \frac{M(\sim l^2)}{W(\sim h^2)} \tag{9.4}$$

So if it is required that the doors must be from a certain type of steel with a maximum allowable σ value, it holds that if the doors are longer, the bending moment increases relative to the square of the length of the barrier. To withstand this bending moment the resisting moment capacity should be increased and this is done by increasing the width of the door. From equation (9.4) can be seen that this has to be increased to a power two as well. This means that the amount of steel needed for for a longer door increases quadratically and for that reason the price of the door increases quadratically.

$$A = h \cdot l \tag{9.5}$$

This holds for a solid door. In case of a truss savings can be made on the amount of steel.

9.2.2. MEMBRANE

Since the membrane is mostly loaded in tension it is thought that the length of the barrier has no or only minor influence on the forces within the membrane. For that reason at increasing gate lengths the tensile fore in the membrane is only dependent on the head. This can also be seen from figure 9.4, the tensile force in the membrane is constant for increasing gate lengths.

9.2.3. EFFECT ON LCC

From section 9.2.1 can be concluded that if the length increases for doors with no reinforcement or truss structure the costs per meter length increase quadratically. This will probably be less for truss doors but it is thought the increase is still above linear. For the membrane the tensile force remain the same and for that reason the costs per meter length stay the same. This makes it very clear that for very long gates inflatable barriers are expected to be less costly. It could be that if the length of the gates decreases, at a certain length doors will be economically preferable over a membrane. More research is needed to find a turning point, and if it is present, at which length doors are less expensive than bellows.

9.2.4. CASE STUDY

This analysis has also been performed for the Hartel location. An outside water level of 9,5 m and an inside water level of 7,7 m is used and the gate length is increased. The results can be seen in figure 9.5. The red dots give the lengths for the two doors of the current Hartel barrier (49,3 and 98 m). It can be seen that these doors are in the more favourable part of the graph; for larger lengths the graph for the doors becomes steeper. Since an inflatable barrier has a lower LCC for the Hartel location (at the more favourable part of the graph for doors) it is expected that this difference in LCC will only become larger for larger gate lengths making the inflatable barrier more favourable. It must be noted that the original Hartel barrier has doors with a truss structure and a highly innovative shape.

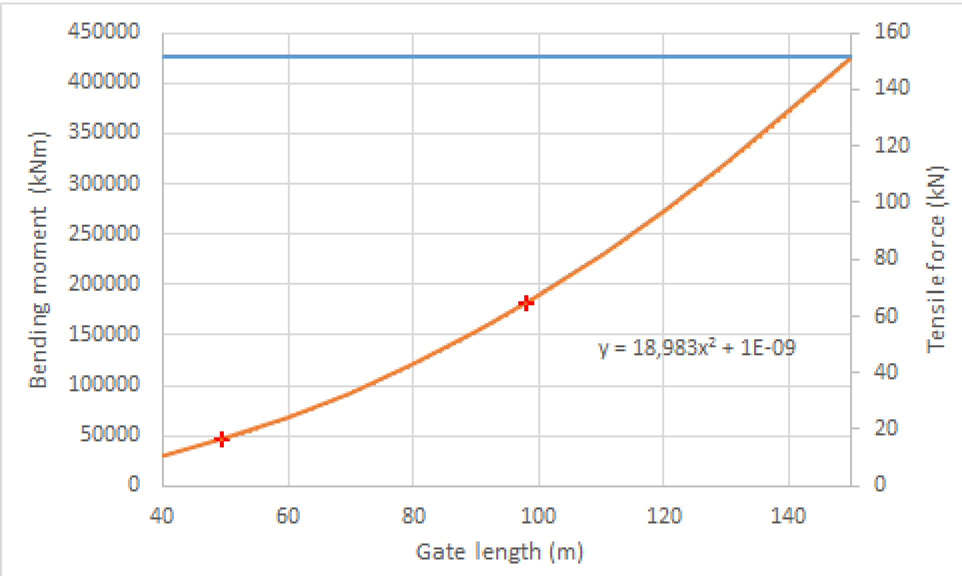

Figure 9.5: Bending moments for doors (orange) versus tensile force in membrane (blue) by increasing gate length for Hartel conditions. The red dots give the lengths of both Hartel barrier doors. In this case a head of 1,8 m (outside 9,5 and inside 7,7 m) is used, corresponding with the Hartel situation[2]

[2]Note: the tensile force for the membrane is also dependent on the water level within the bellow, in this case the tensile force that is used during this thesis for the inflatable Hartel barrier is used (see table 4.8).

9.3. VARYING HEAD

In section 9.2 the impact of longer gates on LCC has been discussed. Within this section the gate length will be fixed and the influence of the head for the LCC is investigated. This is done by calculating the maximum bending moments for the doors and the tensile force in the membrane for increasing heads. In order to do this a fixed outside water level of 10 m is used, the inside water level varies from one to ten meter with steps of 1 m. The bending moments have been calculated with MatrixFrame and the tensile force in the membrane by making use of the spreadsheet presented by Dirkmaat. The results can be found in table 9.2 and figure 9.6, the bending moments are shown in kNm/m since they are per meter length. The model used for the bending moment calculations is schematised in figure 9.7.

Inside water level (m)	Outside water level (m)	Head (m)	Max. moment		Tensile force	
1	10	9	628,37	kNm/m	651,95	kN
2	10	8	621,78	kNm/m	569,62	kN
3	10	7	604	kNm/m	487,14	kN
4	10	6	569,88	kNm/m	406,94	kN
5	10	5	514,18	kNm/m	326,24	kN
6	10	4	439,58	kNm/m	251,91	kN
7	10	3	346,13	kNm/m	173,55	kN
8	10	2	238,75	kNm/m	112,29	kN
9	10	1	121,81	kNm/m	58,01	kN
10	10	0	0	kNm/m	0	kN

Table 9.2: Bending moments for doors versus tensile force in membrane by increasing head

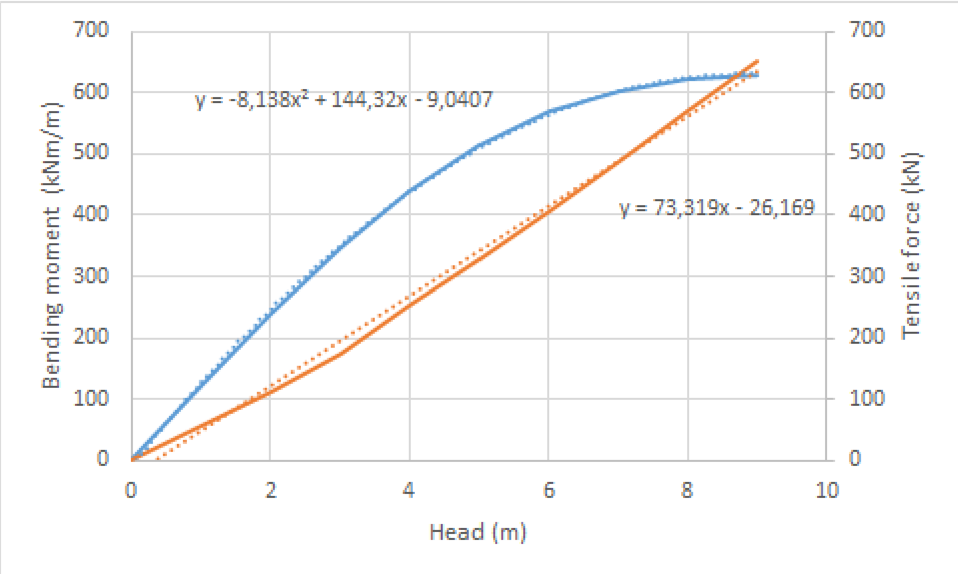

Figure 9.6: Bending moments for doors (orange) versus tensile force in membrane (blue) by increasing head (cross section)

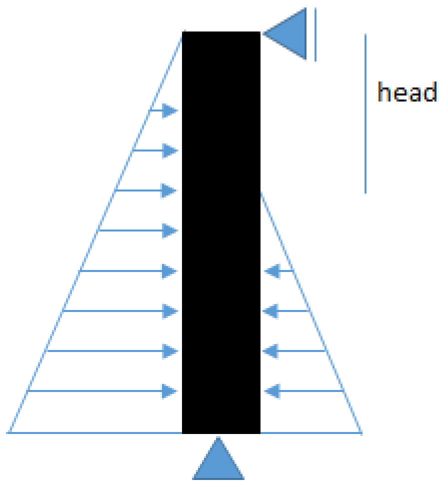

Figure 9.7: Model used for calculating the impact of a larger head for vertical lifting doors (cross section)

9.3.1. DOORS

If the head is increased the bending moment for the doors will increase and approach the asymptotic value for the maximum head. The effect on the bending moment for lower heads is much larger than at higher heads. This can be explained by the fact that the left triangle in figure 9.7, which represent the distributed load due to the outside water level, is constant while the right triangle, which represents the distributed load due to the inside water level, changes. The lower the inside water level the smaller the triangle that can be subtracted from the outside water level. The impact of the inside water level can be calculated by calculating its area. The area, which represents the force, can be calculated by:

$$F = \frac{1}{2}\rho g h^2 \tag{9.6}$$

From this equation can be concluded that the impact for lower head, and thus higher inside water levels represented by h, will be higher.

Although the impact is higher at lower heads, the bending moment is higher at higher heads. If the same theory of section 9.2.1 is used the costs will rise faster at lower heads and the increase in costs will get lower as the head increases.

9.3.2. MEMBRANE

The results for the membrane are calculated by making use of the spreadsheet, this means also an air pressure has to be given. This air pressure is chosen in such a way that the water level within the bellow is 10 cm lower than the inside water level, since this is similar to the Ramspol situation.

For the membrane can be seen that an increasing head leads to an approximated linear increase in tensile force in the membrane. This means that for increasing head the membrane strength should increase linearly. However, this does not mean that the costs increase linearly; it is assumed that the cover thickness on both sides does not have to increase and only the reinforcement increases. From section 3.2.4 can be seen that the cover layers are about 30 % of the material thickness, this means the reinforcement layers are about 70 % of the membrane thickness. If it is assumed that:

- The amount reinforcement is linearly dependent on the forces
- The costs for the extra reinforcement are also linearly dependent on the amount of reinforcement
- The costs for the membrane are only dependent on the amount of material and the prices for the materials are the same

it can be concluded that the costs for the reinforcement of the membrane are about 70 % of the costs of the membrane. So the costs for the membrane would rise with 70 % of the increase in strength which is dependent on the tensile force in the membrane which is linearly dependent on the head. This would mean that the costs for increasing head would rise with 70 % of the increase in head.

9.3.3. Effect on LCC

It seems reasonable to assume that the most relevant part from figure 9.6 for storm surge barriers is the first part with the lowest head difference. The reasoning behind this is that it is possible to a certain extent to regulate the inside water level by using certain closing strategies. Furthermore, a lot of storm surge barriers have an ocean or sea as outside water and a river on the inside. When the barrier is closed, the river discharge will make the inside water level increase. However, if an inland levee fails the inside water level may decrease to a very low level, increasing the bending moment and tensile force.

If only the first half of the graph is taken into account (head 0-5 m) it can be seen that the bending moment increases more than the force within the membrane. This could also mean that the costs increase more. For the membrane has been suggested that the costs increase with 70 % of the required increase in strength. This means that for low head differences the costs for increasing heads rise faster for doors than for membrane. This is off course for doors without a truss section or reinforcement structure. More research is needed to investigate what solution is economically preferable for varying head differences. However, it seems reasonable to assume that the bellows are less costly at increasing head differences for low to medium head differences since the inflatable Hartel barrier has lower LCC for the case study.

9.3.4. Case study

the results for the Hartel conditions are shown in figure 9.8. For this analysis an outside water level of 9,5 m is maintained and the inside water level is varied from 1 to 9 m. The red dots give the situation for the Hartel location (a head of 1,8 m). The Hartel scenario is clearly in the lower hydraulic head part of the graph.

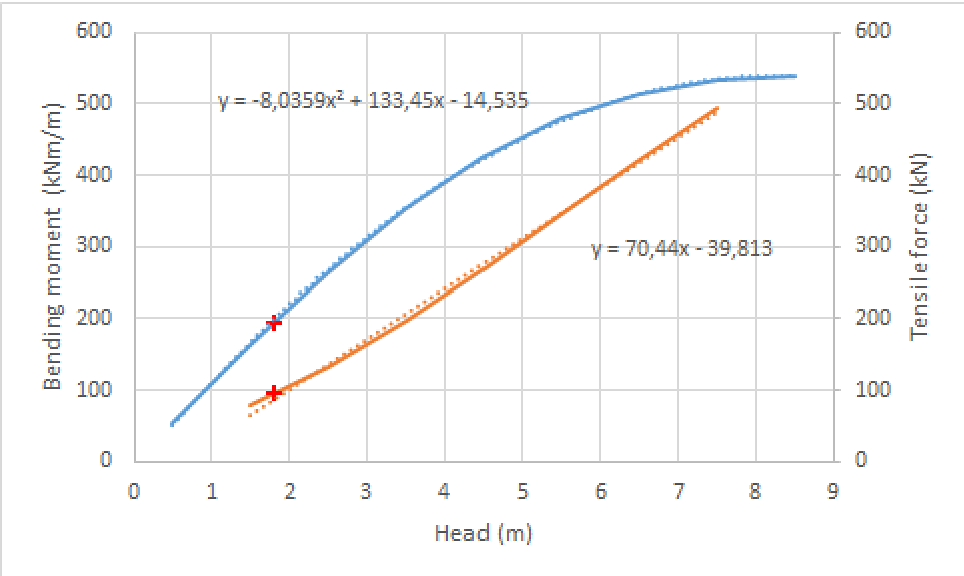

Figure 9.8: Bending moments for doors (orange) versus tensile force in membrane (blue) by increasing head (cross section)

9.4. DEEPER WATER

Within this section the influence of increasing water levels, with a constant head, is on the LCC for both types of barriers. Since global warming is a big issues these days and sea level rise is expected to go faster and faster this is a very relevant analysis. As already has been said, the water levels on both the inside and the outside increase and the head is kept constant. The results can be found in table 9.3 and figure 9.9.

Inside water level (m)	Outside water level (m)	Head (m)	Max. moment		Tensile force	
0	3	3	17	kNm/m	-	kN
1	4	3	39	kNm/m	85,12	kN
2	5	3	71	kNm/m	101,72	kN
3	6	3	111	kNm/m	116,51	kN
4	7	3	159	kNm/m	130	kN
5	8	3	214	kNm/m	143,01	kN
6	9	3	276	kNm/m	156,26	kN
7	10	3	346	kNm/m	170,16	kN

Table 9.3: Bending moments for doors versus tensile force in membrane by increasing water levels and constant head

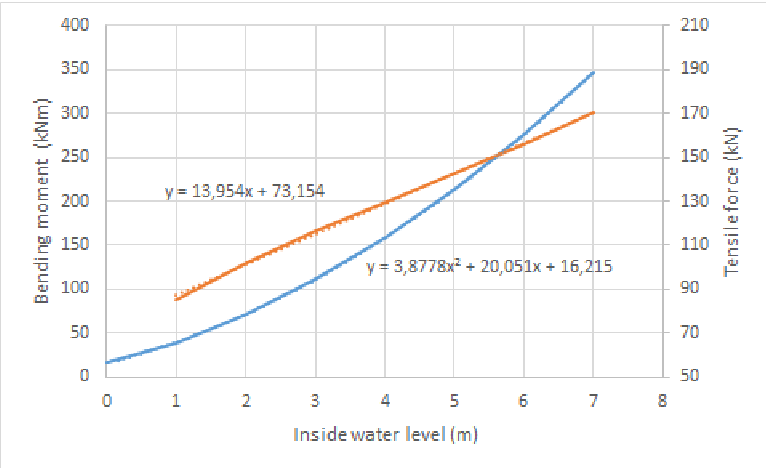

Figure 9.9: Bending moments for doors (orange) versus tensile force in membrane (blue) by increasing water depth (and constant head of 3 m) (cross section)

9.4.1. DOORS

For the doors can be seen that the bending moment increases quadratically compared to the (inside- and thus outside) water level increase. By using the same theory as is used in section 9.2.1 it holds that the amount of steel for the doors and therefore the costs increases quadratically for increasing water depths.

9.4.2. MEMBRANE

The tensile force in the membrane is expected to increase linearly for increasing water levels. For the strength and associated costs holds the same as has been suggested in section 9.3.2.

9.4.3. EFFECT ON LCC

The effects of increasing water levels on LCC are expected to be larger for traditional barriers than for inflatable barriers. It must be further investigated if the inflatable version is less costly for all water depths, but based on the case study this seems reasonable. Unfortunately, this is only one case.

9.4.4. CASE STUDY

For the Hartel location the results shown in figure 9.10 can be found. The head has been kept constant at 1,8 m and both the inside and the outside water level have been increased. The top of the barrier has been kept the same as the outside water level (so it also varies). The spreadsheet could not compute results for inside water levels lower than 3 m (and thus an outside water level of 4,8 m). The red dots show the situation for the Hartel barrier. It can be seen that for higher water depths it is expected that inflatable barriers will be more favourable. It is still unknown if inflatable barrier can be used for deep waters, however Van Breukelen (2013) showed that these barriers are feasible at a depth of 15 m.

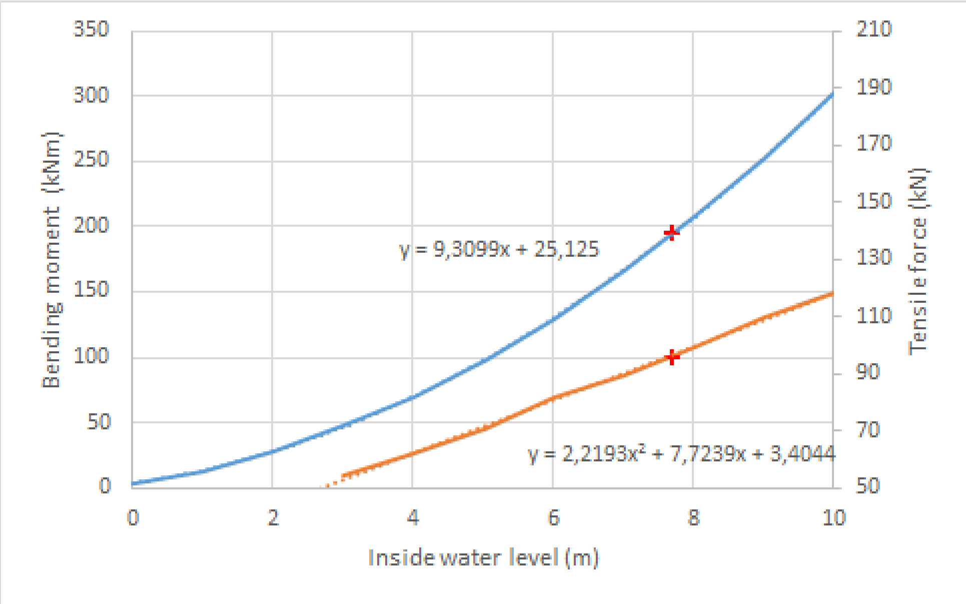

Figure 9.10: Bending moments for doors (orange) versus tensile force in membrane (blue) by increasing water depth (and constant head of 3 m) (cross section)

9.5. SHIP COLLISION

Related to the probability of unavailability is the probability of ship collisions. This section discusses the differences between ship collisions for traditional and inflatable barriers.

9.5.1. DOORS

If a ship hits the solid doors from a vertical lifting gate barrier the doors will most likely receive irreparable damage. The doors will probably buckle due to the enormous concentrated load and may even break. Also holes in the door can appear because of a collision. The collision may also damage the abutments and the guidance rails for the doors and the hoisting/operating system. Figure 9.11 shows examples of lock doors that have been hit by ships.

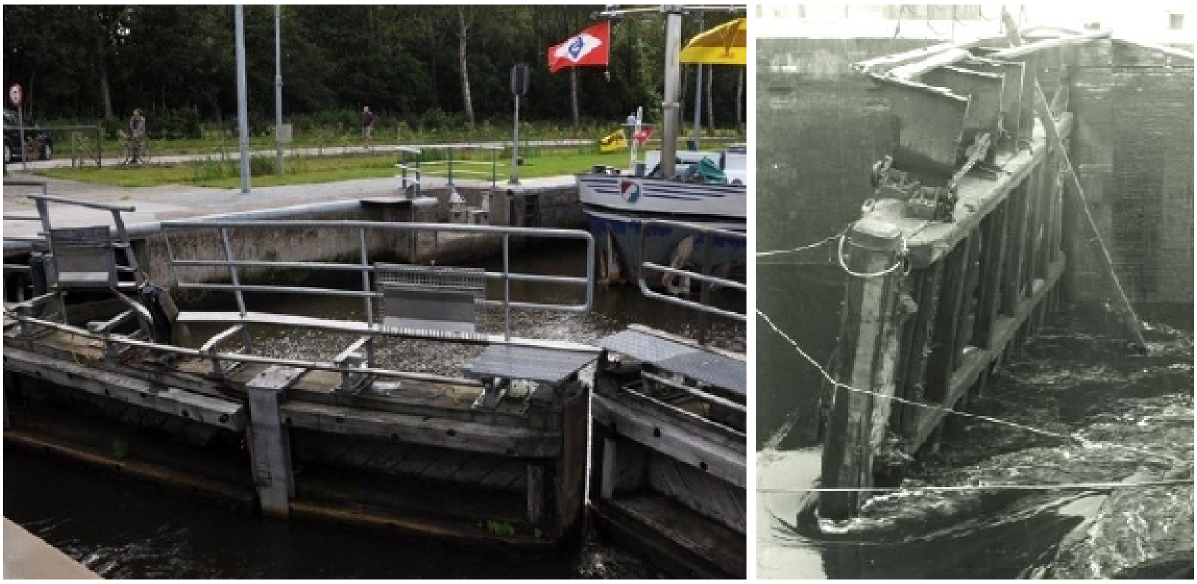

Figure 9.11: Photographs of doors damaged by ship collisions, left shows a lock near Gaarkeuken which has been hit by an inland ship (RTV Noord, 2010) and right shows the door of the Irlam Lock that has been hit by a ship in 1969 (Mrs. Eslie Mullineux, 1969)

9.5.2. MEMBRANE

If it is assumed that a ship will hit the membrane in the horizontal part (not near the abutments), the ship will hit it at its strongest (over-designed) part. The membrane is designed in such a way that it provides the required safety at its weakest point, which is near the abutments and at the anchors. From appendix E can also be seen that the safety for the middle section is by far the highest.

OPEN BARRIER

For an open (inactive) inflatable barrier it has already happened that a ship hit the membrane. This should not have happened, since he membrane is supposed to be stored safely into its bottom recess. However, if this process fails it can happen that a piece of membrane can be hit by a ship (see figure 9.12). According to Horvat & Partners (2010) this has happened for the Ramspol barrier. They claim that in 2004 both a sailing ship and an inland vessel hit a large fold. No significant damage to the membrane was identified.

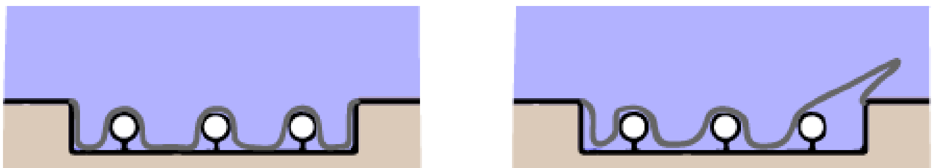

Figure 9.12: Impression of failed storing of the membrane, the left picture shows a correctly stored membrane and the right one shows a fold

CLOSED BARRIER

If the barrier is closed and the bellows are inflated it could happen that a ship does not notice that the barrier is closed or is unable to stop. In this case the ship might hit the barrier. What happens next must be investigated further. Some scenarios might be:

- If it hits the barrier from the upstream (high water) side it could happen that the ship is lifted by the bellow.
- The ship may puncture a hole in the membrane. Depending on the size of the hole the pumps can keep the bellow inflated or not.
- If the ship comes from the downstream (low water) side it may be stopped by the barrier without causing significant damage.
- When a ship hits the bellows at high speed the clamps may fail.

And probably many more scenarios can be thought of. In either case, if the membrane is hit by a ship and the barrier did not fail, the membrane must be investigated as soon as possible. The over-dimensioning might result in safe situation, but due to a collision large longitudinal forces may appear. There is only little strength and reinforcement in the longitudinal direction so it is very unsure what will happen. It must be noted that, in contrast to the doors, the bellows are not fixed and are able to move and adapt. This may also increase the safety level in case of a ship collision.

9.5.3. Effect on LCC

The effects for the LCC are very hard to determine. For the doors it seems most likely that, depending on the weight and the velocity of the ship, significant damage will occur. However it is also likely that the door will be able to fulfill its purpose at least partly. For the membrane it is unknown what will happen. Scale tests may help answering this question. It seems reasonable to assume that, when taking into account the over-dimensioning of the membrane and the shape of the bellow, the damage for inflatable barriers can be lower than for traditional barriers. But if the bellow is punctured the consequences could be more devastating.

9.6. ADAPTABILITY

Section 9.1 already mentioned climate change, sea level rise and an increase in population density. It would be very beneficial if a barrier is able to adapt to changing conditions and requirements without having to build a complete new system. One could think of adapting to larger head differences, higher water levels, increased safety levels, etc. The extent to which it is possible to adapt inflatable or traditional barriers to changing conditions and requirements will be discussed in this section.

9.6.1. DOORS

If, for whatever reason, it is wished for to, for instance, increase the height of the doors to be able to retain higher water levels it will be very difficult to actually do this. Problems associated with this are:

- The loads will increase quadratically for increasing water levels (see section 9.4), and for that reason stronger doors are needed which causes the following problems:
  - Stronger doors usually means thicker doors, it is unsure of they will fit in the existing system.
  - Stronger doors mean heavier doors, the operating system must be able to cope with this increased weight.
  - Since the loads increase it must be investigated if the guiding rails and abutments can handle these loads.
  - The previous point also holds for the foundation; increased loads on the door probably means increased loads for the foundation.
- The doors will be higher and this causes other problems:
  - Since the doors are higher the abutments and/or guiding rails should also be higher to be able to pull the complete door out of the water for the inactive state.
  - If higher doors are required because of higher water levels in general the effect is even larger since the abutments must be high enough to cope with this extra water height as well.

These considerations make it very unlikely that a traditional, vertical lifting gate, barrier can be adapted for higher water levels. So many changes have to be made that a complete new barrier is possibly economically preferable. However, most of these problems could be anticipated on during design by increasing the height of the abutments, over-dimension the foundation, etc.

9.6.2. MEMBRANE

If the same requirement holds for an inflatable barrier, namely increase the water level it is able to retain, the length of the membrane must be increased and the following problems occur:

- A stronger and longer membrane is needed.
- The capacity of the installations (pumps) must be higher to guarantee the same closure and opening time.
- The extra membrane length must be stored in the same bottom recess.
- Higher water levels result in higher loads linearly (see section 9.4). The foundation has to be able to cope with these loads.
- Also the clamps have to be able to cope with these higher loads, but it is assumed that these can be replaced by stronger ones.

Most of these problems can be anticipated on in the design phase: increase the bearing capacity of the foundation and increase the width of the recess to be able to store the extra membrane length. Next to this the pumps will have to be replaced, but it is expected that this should be possible.

9.6.3. EFFECT ON LCC

For both types of barriers can be seen that problems are expected if the barrier must be adapted to changing conditions. For now, only higher water levels are discussed but it is expected that the same type of problems occur for, for instance, higher head differences. Furthermore, it seems reasonable to assume that the occurrence of higher water levels is the the problem that seems most likely to happen.

In the case that the actual parts have to be replaced (the membrane and the doors) the problems for inflatable barriers seem to be easier to cope with than for traditional barriers. The adaptations for vertical lifting gates are technically difficult and aesthetically not preferable. For inflatable barriers the problems seem acceptable if the design allows for it. When the designers of an inflatable barrier over-dimension the foundation and make it possible to store a longer membrane in the same bottom recess, it is mainly a replacement job for several parts.

If it is absolutely necessary to adapt the barrier for certain changed requirements and the only other option is to built a new barrier the effects on LCC could be huge. The costs for the new barrier or the costs for the changes in the current barrier should be included in the LCC. From the analysis above can be concluded that it seems reasonable to assume that designing an inflatable barrier which can cope with changes is easier than for a traditional barrier. For that reason it is assumed that the adaptability for inflatable barriers is higher and the LCC on that aspect will be lower.

9.6.4. CASE STUDY: ADAPTABLE INFLATABLE HARTEL BARRIER

Within this section the construction costs will be calculated for making an inflatable barrier at the Hartel location that is able to cope with a sea level rise of 0,9 meter, which is expected to be the most extreme SLR that can occur in 2100 (see section 9.1). The air pressure is kept constant so the same installations can be used. Table 9.4 gives the input parameters for the spreadsheet for and table 9.5 shows the results for both the inflatable Hartel barrier and the inflatable Hartel barrier that is able to cope with SLR.

	Hartel	Hartel SLR	Unit
h_1	9,5	10,4	m
h_2	7,7	7,7	m
head	1,8	2,7	m
h_{crest} (aim)	9,5	10,4	m
B	16	17	m
L	28	31,5	m
p_{air}	0,3	0,3	bar
h_{in}	6,5	7,4	m

Table 9.4: Input in spreadsheet

	Hartel	Hartel SLR	Unit
h_{crest}	9,79	10,79	m
$h_{crest} - h_1$	0,29	0,29	m
RH_1	98,5	120,7	kN
RV_1	115,2	130,9	kN
RH_2	52,5	117,0	kN
RV_2	142,1	134,3	kN
T	151,5	178,1	kN
ϕ_1	49,5	47,3	degree
ϕ_2	69,7	48,9	degree

Table 9.5: Final design inflatable Hartel barrier compared to inflatable Hartel that can cope with SLR

Table 9.6 shows the design parameters of the adapted inflatable Hartel barrier with the same crest height as the inflatable Hartel barrier. The only differences are the width of the recess and therefore the length of the membrane. Because of these changes also the force in the membrane slightly increased. This is the design of an inflatable barrier with the same crest height as the original Hartel barrier but with a recess that can store a longer membrane and a foundation that can cope with higher forces.

	Adapted Hartel	Unit
h_1	9,5	m
h_2	7,7	m
head	1,8	m
h_{crest} (aim)	9,5	m
B	17	m
L	28,5	m
p_{air}	0,3	bar
h_{in}	6,5	m
h_{crest}	9,79	m
$h_{crest} - h_1$	0,29	m
T	159,8	kN

Table 9.6: Final design adaptable inflatable Hartel barrier

Table 9.7 shows the construction costs for the inflatable Hartel barrier compared to an inflatable Hartel barrier with a stronger foundation and a slightly longer membrane. This longer membrane is needed to cope with the extra recess width. In this way higher water levels can be retained by installing a longer membrane. The costs for the foundation and longer membrane have been calculated by making use of section 6.2.1. Note: these are the costs for an inflatable barrier with the exact same retaining height as the Hartel barrier but with the possibility of placing a longer membrane.

	Inflatable Hartel		**Adapted inflatable Hartel**	
Membrane	€11.700.000	20%	€12.000.000	20%
Abutments	€5.500.000	9%	€5.500.000	9%
Foundation	€2.300.000	4%	€2.900.000	5%
Bed protection	€9.100.000	16%	€9.100.000	15%
Installations	€4.300.000	7%	€4.300.000	7%
Groundwork	€800.000	2%	€800.000	1%
Risk, profit, unforeseen	€10.200.000	17%	10.700.000	18%
Other	€14.500.000	25%	15.200.000	25%
Total sum	**€58.300.000**		**€60.600.000**	

Table 9.7: Construction costs inflatable Hartel and adaptable inflatable Hartel barriers (2014 price level)

Based on these figures can be concluded that an increase in construction costs of €2,3 million makes it possible to place a longer membrane if that is wished for. The maintenance costs will only increase slightly compared to the inflatable Hartel barrier since the costs for replacing the membrane are a bit more and possibly the maintenance costs for the recess increase slightly. This modification in the design makes it possible to change the crest height of the storm surge barrier at every replacement operation for the membrane. The costs for a longer an stronger membrane are expected to be about €15 million[3] which is an increase of only €3 million.

This a very rough calculation to show the possibilities, extra research is required.

[3]Based on an increase in area of membrane (see section 6.2.1) and an increase in costs of 70% of the increase in tensile force (see section 9.3.2).

9.7. No abutments (leakage allowed)

The final option that will be discussed is the possibility of using no abutments as it is suggested by Van Breukelen. This option is only possible for inflatable barriers and not for traditional barriers. So the impact on the LCC of the absence of abutments compared to the option with abutments will be analysed. An impression of this solution is given by figure 9.13.

Figure 9.13: Impression of inflatable barriers with no abutments (Van Breukelen, 2013)

Advantages of this solution are that no local extra length of the membrane is necessary, this means that probably no or only small folds and lower stress concentration will be present in the membrane, no abutments are needed resulting in less impact on the flow pattern when the barrier is deflated and inactive and it is aesthetically preferable since the barrier will be almost entirely invisible when it is inactive. On of the disadvantages is that a lot of leakage in between the bellows will occur. Another possible disadvantage is related to the maintenance and inspection of the membrane. For the Ramspol barrier sheet piles can easily installed in between the abutments for every bellow separately and maintenance in the dry is possible. Furthermore, the bellows can be entered if the bellow is only inflated with air. These advantages of Ramspol will be difficult to maintain for this option.

However, if leakage is allowed, e.g. for the Hartel location, it could be a good alternative. Since (almost) no folds and stress concentrations will be present a less costly membrane could be used. Furthermore the bottom recess can be simpler and no abutments are required. It is assumed that the installations will be stored in the bottom recess somehow. Consequences could be that the bottom recess must be larger and accessible by humans (in order to place the machines and perform maintenance). This would mean that the costs for the bottom recess (which is included in the foundation in this thesis) will probably increase significantly. However, the costs for the abutments will be almost zero.

9.7.1. No abutments

If it is assumed that the costs for the abutments will be zero and that the costs for the foundation will be twice as high (as a very rough first estimate) this results in a saving of €2.1 million for the construction costs (see table 6.13). Furthermore €600.000 per 20 years can be saved in maintenance costs.

9.7.2. Less costly membrane

Next to this the costs for the membrane will be lower and the impact on the LCC will be significant since the replacement of the membrane will also be less costly. If it is assumed that only the SCF will be influenced and that it will be half of the original value (except for the middle section since SCF = 1,0 there) the membrane force for the Hartel barrier will become:

		Middle section	Downstream side	Upstream side	Joints
R_d (kN)		840	1091	1091	947
F_d (kN)	No abutments	197	318	359	297
	Inflatable Hartel	197	636	719	594
R_d/S_d	No abutments	4,27	3,43	3,04	3,19
	Inflatable Hartel	4,27	1,71	1,52	1,59

Table 9.8: Forces and unity check comparison for no abutments and inflatable Hartel (Ramspol membrane). See appendix E for the calculation method

From this table can be seen that, if the same membrane is used, the safety factors (from the unit check) obviously are twice as high. It must be noted that these results are a very rough estimation. More research is needed on the effect on the SCF, next to this it might be that the dynamic coefficient (γ_{dyn}) will increase because of the flow of water in between the bellows. The impact on the costs for the membrane are very hard to determine. The forces in ULS decrease with 50%. If the theory from section 9.3.2 is used the savings would be 35%. For now a conservative decrease in costs of 25% is used. The construction costs for these changes compared to the inflatable Hartel barrier are shown in table 9.9.

	Inflatable Hartel		No abutments	
Membrane	€11.700.000	20%	€8.800.000	18%
Abutments	€5.500.000	9%	-	€0%
Foundation	€2.300.000	4%	€4.600.000	9%
Bed protection	€9.100.000	16%	€9.100.000	19%
Installations	€4.300.000	7%	€4.300.000	9%
Groundwork	€800.000	2%	€800.000	2%
Risk, profit, unforeseen	€10.200.000	17%	€8.600.000	18%
Other	€14.500.000	25%	€12.200.000	25%
Total sum	**€58.300.000**		**€48.400.000**	

Table 9.9: Construction costs comparison for the inflatable barrier with no abutments and the inflatable Hartel barrier (2014 price level)

From these figures can be concluded that about €10 million can be saved for the construction costs. Figure 9.14 shows the discounted maintenance costs for the version with no abutments compared to the inflatable Hartel barrier.

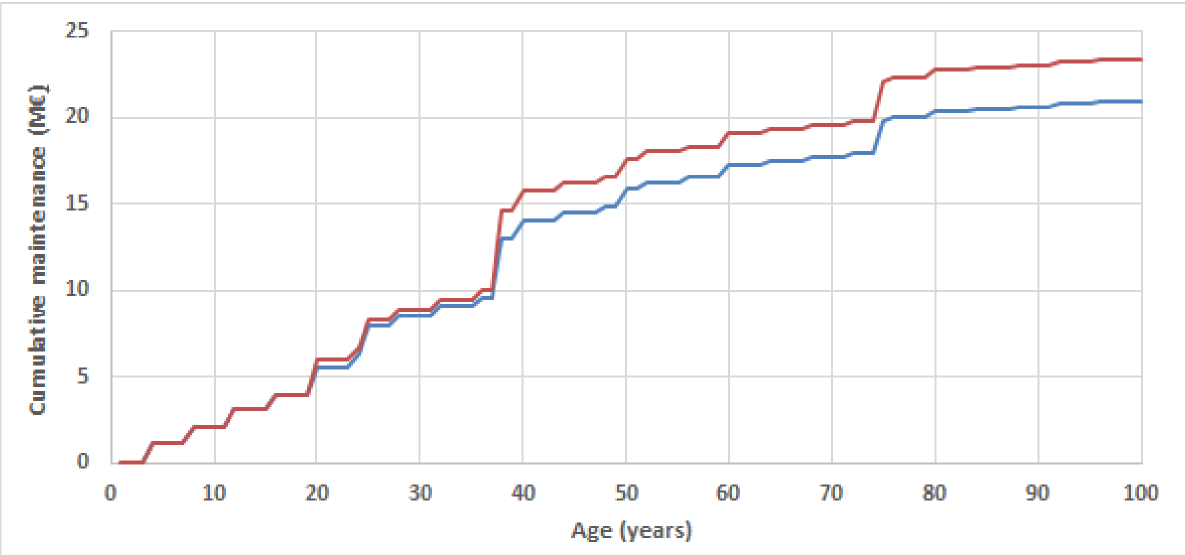

Figure 9.14: Discounted cumulative maintenance costs for the inflatable Hartel barrier (red) and the inflatable Hartel barrier with no abutments (blue) (with a membrane lifetime of 37,5 years)

Table 9.10 shows the construction costs, PV for the maintenance costs and PV for the total costs of the inflatable Hartel barrier and the inflatable Hartel barrier with no abutments. It must be noted that these values are very rough estimates. It can be seen that the main differences are in the construction costs.

Barrier	Construction	PV maintenance	Total PV
Inflatable Hartel	€58.300.000	€24.800.000	€83.100.000
No abutments	€48.400.000	€20.900.000	€69.300.000

Table 9.10: Construction costs and PV values for the inflatable Hartel barrier compared to the no abutments version

It can be concluded that it is probably economically preferable to consider an inflatable barrier without abutments.

9.8. AESTHETICS

Lastly the aesthetic considerations will be discussed. These aesthetic considerations are not direct included in LCC, but in case of an economic comparison the options must meet the requirements, including aesthetics (ISO, 2008). It is very hard to put a cost to aesthetics but they can be analysed qualitatively and scored if it is wished for.

A big advantage for the inflatable barrier over the vertical lifting gate barrier is aesthetics; an inflatable barrier is, except for its abutments[4], invisible during its inactive state. Furthermore, the abutments are relatively small and for that reason probably acceptable for most locations. Vertical lifting gate barriers have to be able to have the doors above the water during the inactive state, this means that the abutments have to be high. Since storm surge barriers are almost always inactive the doors are almost always visible which is also not preferable aesthetically.

Unfortunately it is thought to be impossible to argue about taste. Some people may like the sight and industrial look of a big barrier at some location[5] and others may prefer an almost invisible and smooth barrier. For certain natural areas it is probably preferred to have the almost invisible and interfere as less as possible with nature. Furthermore it is assumed that a larger part of society prefers the option that is least visible. For that reason it has been decided to conclude that aesthetically the inflatable barrier is preferred over the vertical lifting gate barrier.

9.9. GENERAL CONCLUSIONS

This section will summarise the findings of this chapter. Table 9.11 shows the scores per aspect that is treated for both vertical lifting gate barriers and inflatable barriers. The motivation for the scores is given in the itemisation below.

	Vertical lifting gate	Inflatable
Function loss	0	0
Gate length	-	+
Hydraulic head	0	0/+
Water depth	-	+
Ship collision	0	0/+
Adaptability	-	+
No abutments		+
Aesthetics	0	+

Table 9.11: Scores for the different general aspects: - negative score or not feasible, 0 average score or too little information, + positive or very feasible

- **Costs for function loss:**
  Based on this analysis it is very hard to determine which barrier type will have the highest costs for unavailability. There are a lot of uncertainties for both barriers; *a*) it is hard to determine the probabilities of failure for the barriers; *b*) the consequences of failure have a very high uncertainty; and *c*) the failure modes are difficult to determine. For this reason it has been chosen to give both types of barrier a neutral score.

- **Gate length:**
  When it is wished for to have as little abutments as possible or to close great lengths at once a barrier should have longer gate lengths. It is shown that this is probably possible for inflatable barrier since it is thought that the tensile force in the membrane is independent of the length of the bellow. Therefore the inflatable barrier scores a plus. The bending moment in the doors is dependent on the length of the door and increases quadratically. Therefore it is thought that there is a limit to the maximum length of doors and that is why a minus is given. Furthermore, the costs are expected to rise very fast as well for increasing gate lengths.

[4] And possibly they are not necessary, see section 9.7.1
[5] The writer himself likes for instance the sight of the Hartel- or Eastern Scheldt barrier very much

- **Hydraulic head:**
  For larger head differences a slight advantage exists probably for the inflatable barrier, mainly because it is thought that it is unlikely to have a head difference which is larger than 50 % of the outside water level. The reasoning behind this is that the inside water levels can be controlled to a certain extent by the closure strategy. However, it is not a very big advantage and for that reason the traditional barrier is given a neutral score and the inflatable version a slightly positive score.

- **Water depth:**
  Based on these analyses can be concluded that the effects of increased water depths are more disadvantageous for traditional barriers than for inflatable barriers; the bending moment for the doors increases quadratically while the tensile force increases linear for increased water levels. For this reason a plus has been given to the inflatable barrier and the traditional barrier scores a minus.

- **Ship collision:**
  For ship collisions can be said that it is likely that significant damage will occur for barriers with doors and that it is unknown what will happen for inflatable barriers. There are reasons to believe that an inflatable barrier will have more resistance for ship collisions, but what will happen is largely unknown. So a small positive score is given to the inflatable barrier versus a neutral score for the traditional barrier.

- **Adaptability:**
  The possibilities for adaptation to new requirements seem to be much greater and more realistic for inflatable- than for traditional barriers. However, this is probably only possible if it is included during the design phase. Section 9.6.4 shows that the construction costs seem to increase by only €2,3 million (or about 4%) if the inflatable Hartel barrier is constructed in such a way that it can be adapted to a SLR of 0,9 meter.

- **No abutments:**
  An inflatable barrier without abutments, as it is proposed by Van Breukelen (2013), is probably about €14 million less costly over its total lifetime than the version with abutments, which is about 15%. If leakage is allowed this could be an interesting option. More research is needed. Obviously no score is given for the traditional barriers since these cannot be built without abutments

- **Aesthetics:**
  Aesthetically it is assumed that an inflatable barrier is preferred although it is off course a matter of taste. The assumption is that more people will prefer an almost invisible barrier and for that reason the inflatable version is preferred.

Based on the predictions of Intergovernmental Panel on Climate Change (IPCC) the sea levels will probably rise the coming 80 to 100 years and this will lead to increased water levels or increased hydraulic head differences. The effects for inflatable barriers are expected to be less disadvantageous compared to vertical lifting gate barriers. Furthermore, inflatable barriers can probably be designed in such a way that they can be adapted to changing water levels for just a small increase in construction costs. This makes them economically and probably structurally a very interesting alternative.

10

Conclusions and recommendations

This chapter will elaborate on the conclusions from this thesis and discusses some recommendations for future research in order to improve the the reliability of the findings.

10.1. Conclusions

The conclusions for this thesis will be split up into two parts: the answers to the research questions and the updated version of table 3.1.

10.1.1. Research questions

For this thesis one main research question and several related sub questions have been determined. First the main question will be answered and then the sub questions will be answered. For most questions answers are presented for the case study at the Hartel location and answers for the general case, mainly based on chapter 9.

Main research question

Taking Life Cycle Costs into account, might an inflatable barrier be economically preferable to a 'traditional' vertical lifting gate barrier?

During this thesis a case study has been conducted: an inflatable barrier has been designed for the same location and requirements as hold for the Hartel barrier. The purpose of this case study was to make a fair comparison between the two barrier types and to have a starting point for more general conclusions. The answer for this question has been split up in two parts; first the conclusions with regard to the case study will be discussed and then the general conclusions will be drawn.

Case study conclusions

The conclusions for the case study is rather straight forward and follow from the deterministic results (section 7.8) and the sensitivity analysis (section 8.3). From both analyses can be concluded that the inflatable Hartel barrier is about 15% to 20% less costly than the original Hartel barrier over its total life time. Furthermore, both the construction and maintenance costs are lower for the inflatable barrier. For these reasons it is concluded that an inflatable barrier is economically preferable for the Hartel location.

From the sensitivity analysis can also be concluded that it is for 95% certain that the LCC for the Hartel barrier will be higher than €95,7 million and that it is for 95% certain that the LCC for the inflatable barrier are lower than €87,5 million. This strengthens the conclusion earlier drawn that an inflatable barrier at the Hartel location is economically preferable (see table 10.1).

Furthermore, it can be concluded from the sensitivity analysis that the coefficients of variation are almost the same and for that reason the dispersion of the two probability density functions are rather similar. Which means that the values have about the same reliability.

Barrier	Construction	PV maintenance (mean)	Total PV (mean)	PV (5%)	PV (95%)
Hartel	€63.700.000	€36.600.000	€100.300.000	€95.700.000	€104.900.000
Inflatable Hartel	€58.400.000	€24.700.000	€83.100.000	€78.700.000	€87.500.000

Table 10.1: Present Value for construction costs, maintenance costs and the total LCC and the 5% and 95% confidence levels (2014 price level)

GENERAL CONCLUSIONS

General aspects have been discussed in chapter 9. Although most real impacts on the LCC are unknown for the analysed phenomena (function loss, gate length, hydraulic head, water depth, ship collisions, adaptability, no abutments and aesthetics) the conclusions based on mostly qualitative analyses are in favour of an inflatable barrier.

The conclusions for longer gates and deeper water situations can be seen as rather certain. For both phenomena the increase in bending moments for a door structure rise quadratically while the force in a membrane only rise linearly. When this is related to the case study and when taking into account the result that an inflatable barrier is already 19% less costly, it is expected that this difference in LCC will only rise for deeper water or longer gates.

Very interesting could be the possibilities for adaptation. It is thought that an inflatable barrier could be adapted to other circumstances or requirements by replacing the membrane by a longer/shorter and stronger/less strong version and possibly replacing the installations and clamps. The only requirement is that the foundation must be able to cope with these increasing loads. This is something that could be included during the design phase and in that way the barrier can be changed for relatively low costs.

SUB RESEARCH QUESTIONS

For the sub questions the conclusions have again been split up into conclusions for the case study and conclusions in general.

1. ***What are the governing factors that influence the LCC for both types of barriers?***

CASE STUDY CONCLUSIONS

For the case study the factors that are most influential for the results can be found in the maintenance costs. Since the construction costs for the Hartel barrier are only known as lump sum it is very difficult to determine cost drivers. So only the maintenance costs are taken into account for now.

From tables 10.2 and 10.3 can be seen that the inflatable version has three cost drivers and the Hartel barrier has four[1]. For the inflatable Hartel barrier the control system and the membrane are by far the most dominant factors and then comes the operating system. This is the same for the Hartel barrier when doors are considered.

It can be concluded that the governing parameters are the membrane, doors and operating system. Improving the lifetimes or decreasing the costs would be very beneficial for the LCC.

[1] If it is assumed that cost drivers are responsible for ≥ 10% of the total.

Cost group	PV maintenance	Relative to total
Groundwork	€130.000	1%
Bed protection	€1.210.000	5%
Foundation	€270.000	1%
Offices	€170.000	1%
Guidance ships	€1.480.000	6%
Abutments	€1.150.000	5%
OS	€2.960.000	12%
Control system	€10.920.000	44%
Membrane	€6.410.000	26%
Total	€24.800.000	

Table 10.2: Influence of cost groups on total maintenance PV for the inflatable Hartel barrier (deterministic, 2014 price level)

Cost group	PV maintenance	Relative to total
Groundwork	€130.000	0%[2]
Bed protection	€1.350.000	4%
Foundation	€670.000	2%
Offices	€170.000	0%[2]
Mooring dolphins	€490.000	1%
Abutments	€4.050.000	11%
OS	€7.960.000	22%
Control system	€10.920.000	30%
Doors	€10.790.000	30%
Total	€36.500.000	

Table 10.3: Influence of cost groups on total maintenance PV for the Hartel barrier (deterministic, 2014 price level)

GENERAL CONCLUSIONS

For the general conclusions the findings of chapter 9 will be used. From this chapter can be concluded that barrier length and water depth are the two governing factors. With regard to the water depth must be noted that it is still unclear what the limit is for inflatable barriers. For this reason the barrier length is chosen to be the governing factor for choosing between the two types of barriers.

2. ***Would an inflatable barrier have been an economically preferable alternative to the Hartel barrier when taking LCC into account?***

CASE STUDY CONCLUSIONS

As already has been concluded at the main research question: an inflatable barrier at the Hartel location and with the same requirements as hold for the current Hartel barrier would be about 19% less costly and for that reason economically preferable.

3. ***Generally speaking, what can be said about the LCC comparison between inflatable barriers and vertical lifting gate barriers?***

GENERAL CONCLUSIONS

In general can be said that it seems that inflatable barriers are preferable over traditional vertical lifting gate barriers for multiple reasons (see chapter 9):

- The failure modes might be less dangerous which would result in lower costs for unavailability. However, there is much unknown about the failure modes of inflatable barriers, so more research is needed.
- When it is desired to have as little abutments as possible or to close great lengths at once inflatable barriers are preferable over traditional barriers
- For larger head differences a slight advantage exists probably for the inflatable barrier. The main reason is that it is thought to be unlikely to have a head difference which is larger than 50 % of the outside water level, since the inside water level can be partially controlled by the closing strategy.
- The effects of increased water depths are more disadvantageous for traditional barriers than for inflatable barriers; the bending moment for the doors increases quadratically while the tensile force increases linear for increased water levels.
- For ship collisions can be said that it is likely that significant damage will occur for barriers with doors and that it is unknown what will happen for inflatable barriers. There are some reasons to believe that an inflatable barrier ensures a higher safety for ship collisions.

[2] The contribution is 0% due to rounding, actually it is of course a very small percentage less than 0,5 %

- The possibilities for adaptation to new requirements seem to be greater for inflatable than for traditional barriers. However, this is probably only possible if it is included during the design phase. It is found that for an increase in construction costs of €2,3 million (or 4%) an inflatable barrier can be constructed at the Hartel location that can be adapted for rising water levels.
- An inflatable barrier without abutments as it is proposed by Van Breukelen (2013) is probably less costly than the version with abutments. If leakage is allowed this could be an interesting option. More research is needed.
- Aesthetically it is assumed that an inflatable barrier is preferred although it is off course a matter of taste. The assumption is that more people will prefer an almost invisible barrier and for that reason the inflatable version is preferred.

4. ***What is the effect on LCC of the inflatable barrier for varying lifetimes of the membrane?***

CASE STUDY CONCLUSIONS

This phenomenon has been addressed in section 7.6. It can be concluded that the lifetime of the membrane is of great impact of the LCC for the inflatable barrier. But it can also be seen that for all chosen lifetimes the inflatable barrier still has significantly lower costs than the original Hartel barrier. If the lifetime further decreases under 20 years the effects can be seen in figure 10.1. It can be seen that the maintenance costs for the inflatable barrier are still less than for the original barrier for a lifetime of 20 years. For a lifetime of 15 years the maintenance costs for an inflatable barrier will be about €5 million more. Since the construction costs for an inflatable barrier are expected to be €5 million less than for the original barrier (see section 6.4) the LCC will be almost the same.

From this can be concluded that an inflatable barrier is expected to have lower LCC than the original Hartel barrier if the membrane lifetime is higher or equal to 15 years.

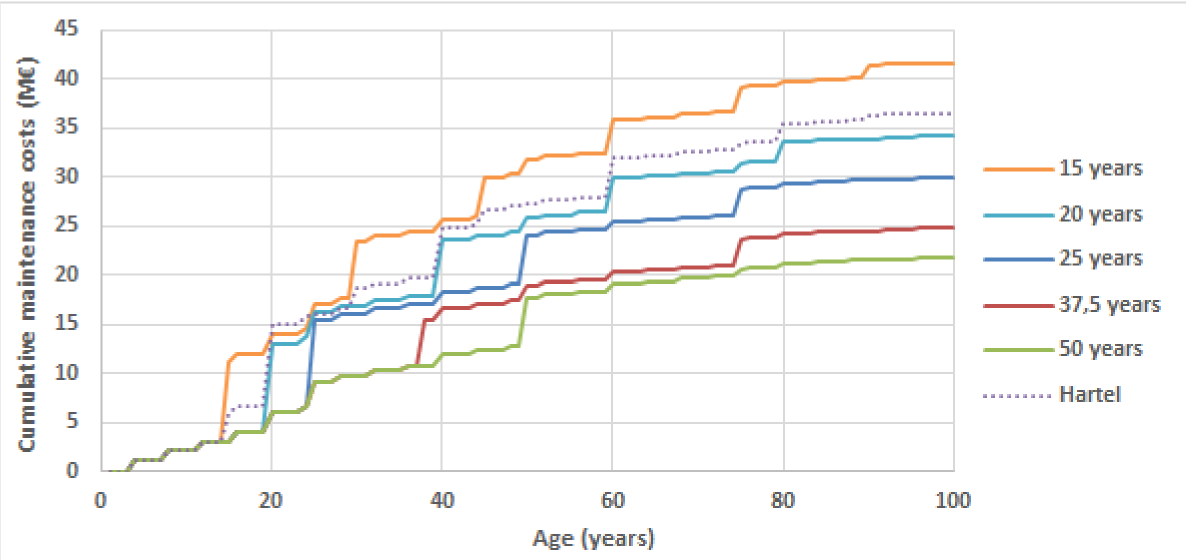

Figure 10.1: Smaller failure probability for smaller standard deviation. In orange the failure probability for distribution A > in red the failure probability for distribution B

GENERAL CONCLUSIONS

In general can be said that the lifetime of the membrane is of great influence on the LCC for the inflatable barrier. The experiences with the membrane of the Ramspol barrier can be used as indicator for the membrane lifetime and should for that reason be monitored.

5. ***What is the influence of the discount rate on the LCC comparison?***

CASE STUDY CONCLUSIONS

The influence of the discount rate has been analysed in section 7.7. It has been concluded that the net benefits of a higher discount rate are higher for the original barrier compared to the inflatable one, but relatively the benefits higher for the inflatable Hartel barrier. The differences were small. Relatively the inflatable barrier slightly benefits from a higher discount rate.

GENERAL CONCLUSIONS

In general can be said that a high discount rate will be favourable for assets with low construction costs, a short life and high recurring costs. A low discount rate will have the opposite effect (Kumar et al., 2004). Since both types of barriers have a similar construction costs and recurring maintenance costs the effect is expected to be low.

6. ***What maintenance regime is ideal for inflatable barriers?***

CASE STUDY CONCLUSIONS

A maintenance regime for a barrier as a total cannot be determine. A decomposition in parts and having a maintenance regime for each part is essential. It can be beneficial to combine certain maintenance activities if they are for instance in consecutive years. It might be less costly to perform certain maintenance operations before they are required so that they can be combined with other maintenance works. Not only the maintenance works for the asset but also for the surroundings should be included in the decision making. The decomposition and associated strategies can be found in table 10.4, it must be noted that this decomposition is rough and only useful on a strategic level. A more detailed decomposition should be used to end up with the best maintenance strategy. The different maintenance regimes that can be used can be found in section 7.2.

Part	Maintenance strategy
Membrane	State based
Doors	Time based / State based
CS	Time based
OS	Load based / Time based
Abutments	State based
Guidance ships	Load based / Time based
Mooring dolphins	Failure based
Offices	Time based / Failure based
Foundation/recess	Time based
Bed protection	State based
Groundwork	State based

Table 10.4: Maintenance strategies for the parts (see chapter 7 for the background and motivation)

GENERAL CONCLUSIONS

The conclusions from the case study hold also in general. A solid maintenance strategy can be found by a proper decomposition and by combining certain maintenance operations.

7. ***What are the most uncertain factors and what can be done to improve their uncertainties?***

CASE STUDY CONCLUSIONS

Probably the most uncertain factor is the lifetime of the membrane. This is also illustrated in tables table 10.5 and table 10.6 (see section 8.3.2). The design lifetime is 25 years, but the expected lifetime is higher and could be up to 50 years (this thesis used a mean lifetime of 37,5 years). This can have a serious impact on the LCC of inflatable barriers. Improving the certainty of the lifetime could be done by researching this phenomenon more and by keep a close eye on the deterioration of the membrane at the Ramspol barrier.

Part	σ_X (M€)	Δ
Doors	2,21	0,79
CS	1,31	0,47
OS	0,9	0,32
Z	2,79	-
Sum α^2		0,95

Table 10.5: Relative influence of coefficients for the Hartel barrier for the doors, CS and OS

Part	σ_X (M€)	α
Membrane	2,31	0,87
CS	1,28	0,48
OS	0,18	0,07
Z	2,67	-
Sum α^2		0,99

Table 10.6: Relative influence of coefficients for the inflatable Hartel barrier for the membrane, CS and OS

Furthermore, it can bee seen that also the control system and doors have a high relative influence and focussing on improving their reliability should be a priority.

GENERAL CONCLUSIONS

Based on chapter 9, the most uncertain factors in general are:

- Failure modes and failure probabilities for both barriers. These influence the costs for unavailability and reliability of the barriers.
- The effects of increasing the length of the gates of inflatable barriers. It is assumed that the tensile force in the membrane is not influence by the length of the gates, however, this assumption is not substantiated by calculations or models.
- Based on Van Breukelen (2013) can be concluded that inflatable barriers are feasible for depths up to 19 m. More research is needed to substantiate this claim and to investigate if inflatable barriers are feasible for even deeper waters.
- The effects of ship collisions for inflatable barriers. This would be relevant information for the failure probability of the barrier.

10.1.2. UPDATED TABLE TABLE 3.1 - BARRIER TYPE COMPARISON

Chapter 3 starts with a short overview and comparison of different barrier types. The comparison has been prepared by Dircke et al. (see table 3.1). Some of the scores for inflatable barriers are questioned and for that reason these scores are updated based on the findings of this thesis. The substantiation of the scores can be found below.

	Mitre gate	Vertical lifting	Flap	Horizontal rotating	Vertical rotating	Inflatable
Span > 30m	-	+	+	+	+	+
Span > 100 m	-	-	+	+	-	**+**
Water depth > 10 m	+	+	+	+	+	**+**
Impact upon landscape	+	-	+	+	-/+	+
Maintenance	+	+	-	0	+	**+**
Currents and waves	-	+	0	0/+	0/+	0
Closure time	+	+	+	+	+	**+**
Space required	+	+	+	-	+	+
Colliding ships	0/-	+	+	0/-	+	0
Reliability	-/+	+	0/+	-/+	+	0
Clearance height	+	-	+	+	-/+	+

Table 10.7: Updated version of table 3.1, the characters in italic and bold have changed compared to table 3.1: - Not favorable up to not feasible, 0/- Below average/vulnerable, 0 Average/possible, 0/+ Above average, + Favorable/proven technology, -/+ Score depends on design choices and conditions (based on Dircke et al. (2012))

Van Breukelen (2013) showed that bellows with a span of 250 m are feasible. For that reason the requirement "Span > 100 m" has been changed to a "+" from a "-".

Van Breukelen (2013) also found that inflatable barrier for a depth of 15 m are a feasible solution and for that reason the requirement "Water depth > 10 m" has been changed to a "+" from a "-".

This thesis shows that maintenance for an inflatable barrier is expected to be less costly than for a traditional barrier. Jongeling (2005) claims that maintenance regimes for inflatable barriers are preferable over other options. For these reason this requirement has been changed from a "0" to a "+".

The closure time for Ramspol is 30 to 60 minutes (Bouwdienst Rijkswaterstaat, 2007; Jongeling, 2005). This is faster than traditional barrier like the Eastern Scheldt barrier (82 minutes (ir. K. Steenepoorte, 2014)) or the horizontal rotating barrier (closing the Maeslant barrier takes more than 2 hours (Rijkswaterstaat, -)). Since these types of barrier scored a "+" it has been decided to give inflatable barriers the same score.

10.2. RECOMMENDATIONS

To improve the reliability of the conclusions and this thesis extra research should be performed. This section will provide a few topics of research which are thought to be most interesting with regard to this thesis.

10.2.1. BETTER DATABASE FOR (MAINTENANCE) COSTS

For this thesis information about maintenance and construction costs for the different barriers was essential. It was found that getting this information was really difficult for multiple reasons. It seemed that there was no database or complete overview of the costs per barrier divided in certain groups and organisations with informations were hesitant of sharing this information. Although this is understandable it is also thought to make it very difficult to perform analyses like this one which can be very useful to e.g. compare alternatives. The result is that it will be more difficult to make a decision on economical grounds. It would be very beneficial for LCC comparisons, and probably for decision making parties (like Rijkswaterstaat in the Netherlands) in general, if there was an (open) database with cost figures for all types of barriers.

10.2.2. INCLUDE OTHER BARRIER TYPES

Within this thesis a comparison is made between inflatable barriers and vertical lifting gate barrier. However, many more barrier types exist (see figure 3.1 for some of the other options). This thesis may help when a decision between these types of barriers is required and also may provide input for decision making if more barrier types are included. However, including more barrier types would make the analysis better and could provide understanding of the cost drivers for all barrier types.

10.2.3. INCLUDE MORE CASE STUDIES

To improve the reliability of the findings more case studies should be performed to compare LCC for inflatable- and vertical lifting gate barriers. By performing more case studies a wider spectrum of effects can be studied. It is thought that a small number of case studies, or in this case only one case study, cannot be used to draw conclusions in general. By performing more case studies with this procedure the reliability can be improved.

10.2.4. INVESTIGATE WHAT HAPPENS FOR SHIP COLLISIONS WITH INFLATABLE BARRIERS

There is very little known of ship collisions for inflatable barriers. One (or two) ship(s) have hit the membrane during its inactive state because the membrane was not stored properly. A collisions with an inflated bellow has not happened and has not been investigated by, for example, scale test. Since it is argued in section 9.5 that it might be possible that inflatable barriers are able to cope with (minor) ship collisions it would be very good to investigate this further. It could lead to lower safety factors or lower probabilities of failure for the same barrier.

10.2.5. INVESTIGATE THE FEASIBILITY FOR INFLATABLE BARRIERS WITHOUT ABUTMENTS

This option has been proposed by Van Breukelen and if it works it could be a very good solution for certain locations. The LCC is expected to be significantly lower in this case compared to inflatable barriers with abutments. A prerequisite is that the requirements must allow for leakage. Since the first impressions of the possibilities seem promising, more research and maybe scale tests should be performed to investigate the feasibility of this design. Issues with water flowing in between the bellows, maintenance and the locations of the installation should be addressed.

10.2.6. COLLECT DATA AND OBSERVE THE BEHAVIOUR OF THE RAMSPOL BARRIER

The Ramspol barrier is currently the only inflatable dam that is built to work as a storm surge barrier. Some conservative assumptions are made during the design phase. By monitoring what happens to the materials (membrane, clamps, etc.) designs for future inflatable barriers may be less conservative. Furthermore, problems must be noted so future designs can be improved and hopefully have less drawbacks. The signs are very promising so far. Lastly, the costs during its lifetime should be monitored to check whether it is actually an economically preferable solution, this is also recommended by Bouwdienst Rijkswaterstaat in 2007 but it is unclear if this really happens (see section 10.2.1).

10.2.7. INVESTIGATE THE POSSIBILITIES OF AN INFLATABLE BARRIER WHICH ALLOWS OVERFLOW

The Ramspol barrier is not designed to work as weir and only allows overflow due to waves. During this thesis a design is made for an inflatable barrier that should allow for overflow during design conditions. The effects on for instance the required membrane strengths are unknown. Since inflatable dams are used as weirs it should be possible to design an inflatable barrier that allows overflow. More research on this matter is required.

10.2.8. CREATE A 3-D FEM MODEL

All calculations are still based on the spreadsheet model, which is the only model available to calculate the shape of the membrane. A disadvantage is that this model calculated the expected tensile force in the undisturbed region due to static loads. Also length effects, if present, can not be shown by this model. In order to increase the reliability of the calculations and to check the effects of for instance longer gates or deeper water a 3-D FEM should be created.

APPENDICES

A

KAUFMAN'S LIFE CYCLE COST FORMULATION

Figure A.1 shows Kaufman's LCC formulation schematically.

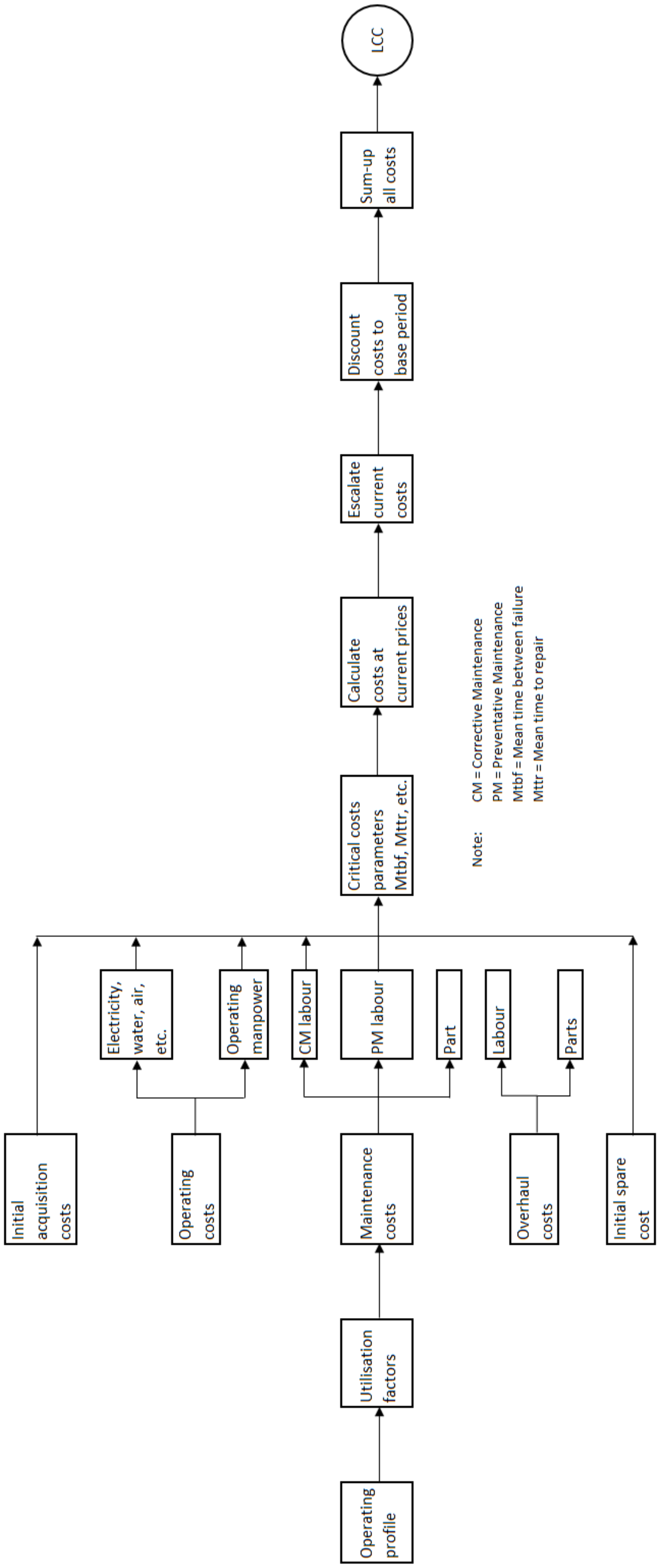

Figure A.1: Kaufman's life cycle cost formulation (Woodward, 1997)

B

TYPICAL SCOPE OF COSTS FOR LCC AND WLC

Figure B.1 shows the typical scope of costs for WLC and LCC according to ISO (2008).

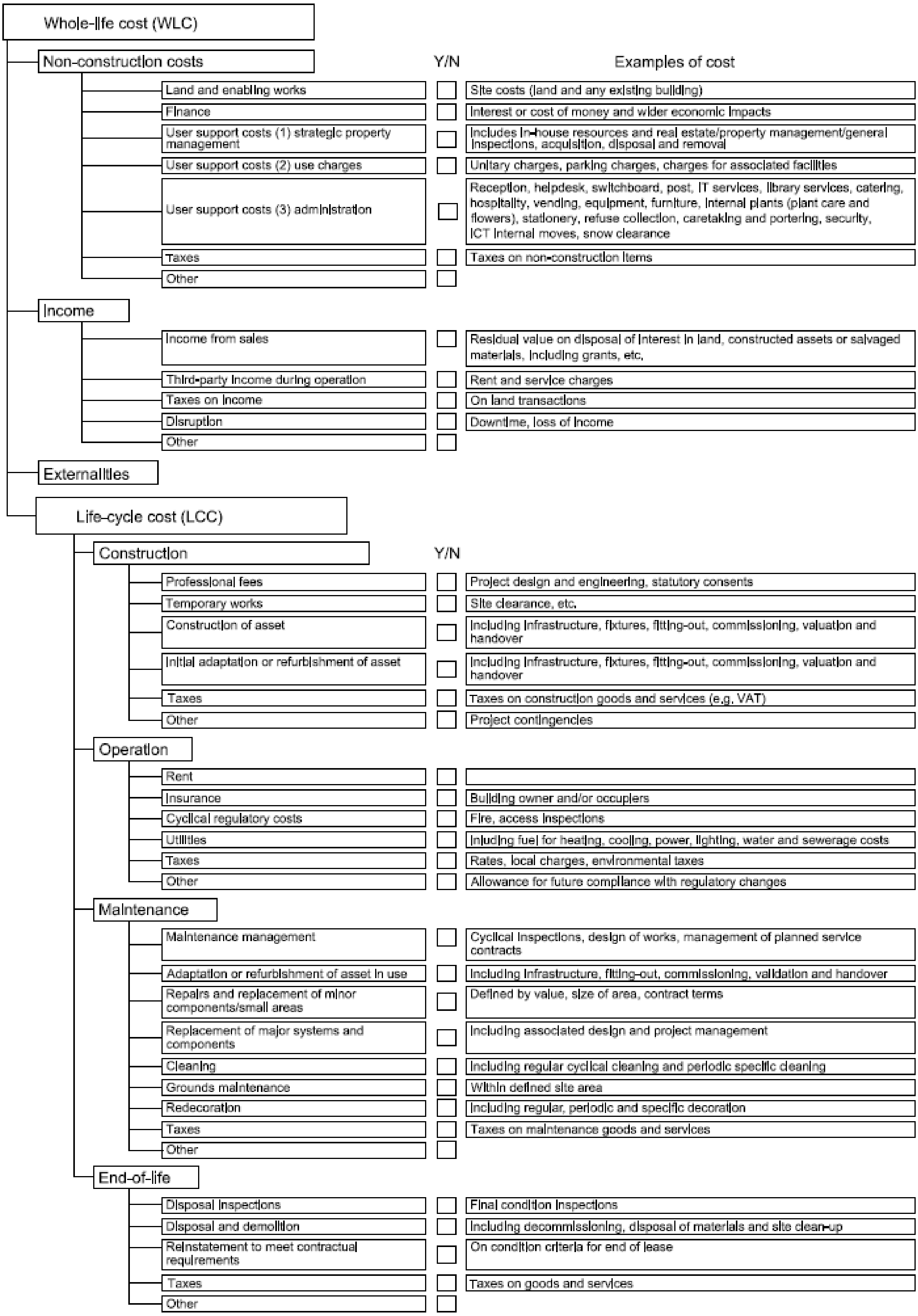

Figure B.1: Typical scope of costs (ISO, 2008)

C

THE THREE LEVELS OF ANALYSIS AT DIFFERENT STAGES OF THE LIFE CYCLE

Figure C.1 shows the three different levels of LCC analyses according to ISO (2008).

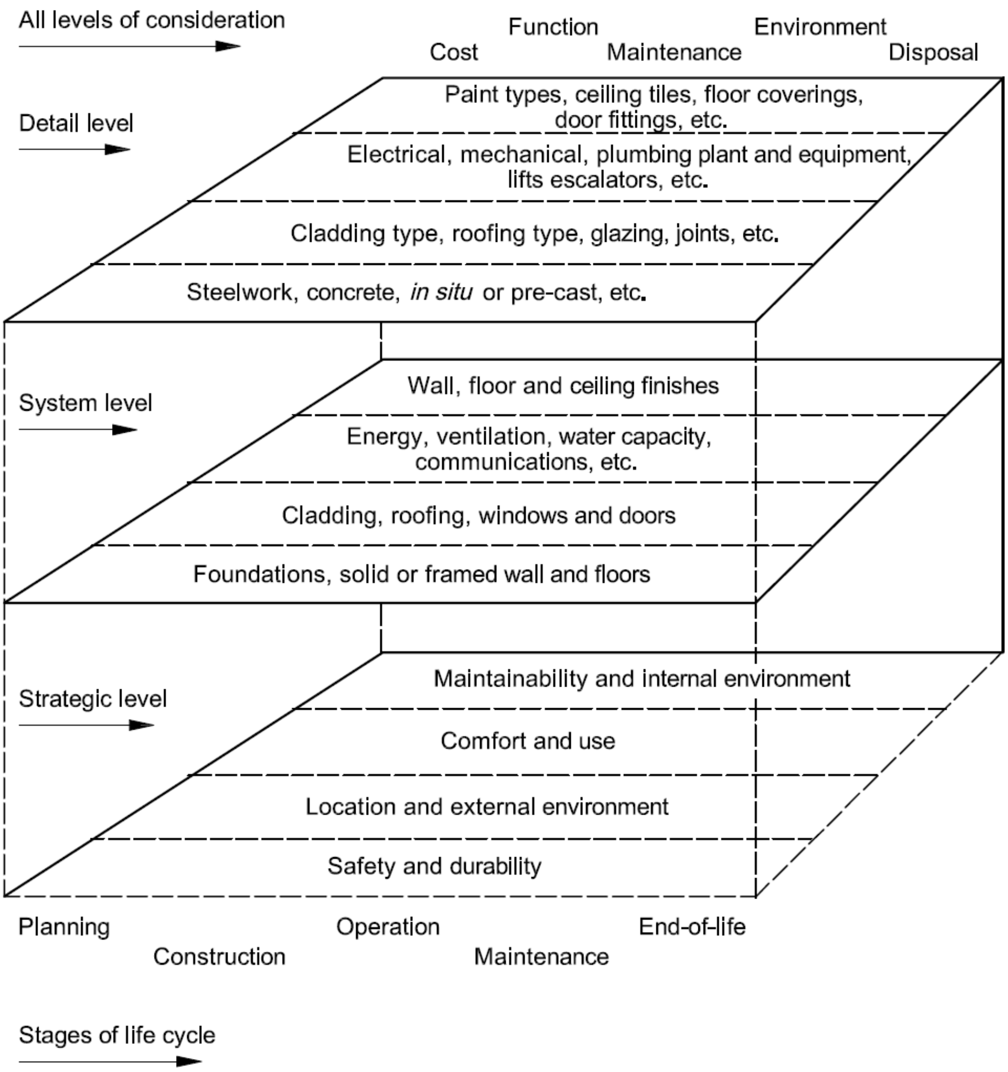

Figure C.1: Different levels of analysis at different stages of the life cycle (ISO, 2008)

D

Calculation of design force and strength membrane

D.1. Design rules

D.1.1. General design formula

The general design formula that was found during design of the Ramspol barrier is given in equation (D.1).

$$R_d = \frac{R_t \cdot SCF_{test}}{\gamma_{mat}} \geq F_d = \gamma_{dyn} \cdot SCF \cdot F_{stat} \tag{D.1}$$

With R_t is the tensile strength of the membrane (kN/m), SCF_{test} is a factor which represents the ratio between the external uniform load and the maximum sheet strength at failure, γ_{mat} is a material factor, F_{stat} represents the static membrane force in 2-D (kN/m), γ_{dyn} is a factor to take dynamic effects into account and SCF is factor that is found by a FEM calculation and takes into account peak stresses.

A unit check can provide information about the safety in a very clear way. The unit check is shown in equation (D.2).

$$\frac{R_d}{F_d} \geq 1{,}0 \tag{D.2}$$

D.1.2. Design factors

Table D.4 shows the design factors that have to be taken into account. As can be seen, the factors differ for different characteristic locations.

	Middle section	Downstream side	Upstream side	Joints
γ_{mat}	1,2	1,2	1,2	1,3
γ_{dyn}	1,3	1,2	1,3	1,3
SCF	1,0	3,5	3,65	3,65
SCF_{test}	1,0	1,35	1,35	1,38
γ_r	1,05	1,0	1,0	1,0

Table D.1: Design factors for load and strength calculations for inflatable barriers (based on van Breukelen (2013))

To take dynamic effects into account the dynamic coefficient y_{dyn} has been determined, i.a. by scaled tests. For both the upstream and the downstream sides y_{dyn} has been determined. For the downstream situation a value of 1.2 is found and upstream a value of 1.3 is found.

The forces for the sloped sections are extremely difficult to calculate and for that reason a 3D FEM has been used to determine a coefficient to take this into account. Within this coefficient also the small wave clamps are included. The forces increase significantly due to the slopes and clamps compared to the forces in the horizontal sections. SCF (stress concentration factor) is the ratio between the forces in the horizontal part and the biggest force in the membrane in the sloped parts. Because of the relative high value of SCF it is very important to calculate the forces for the horizontal part as accurately as possible. With the same method also a factor for the strength has been determined (SCF_{test}).

The material factor is determined in a semi probabilistic way: $\gamma_{mat} = e^{\alpha_R \cdot \beta \cdot V_R}$ with $\alpha_R = 0{,}8$, $\beta = 4{,}26$ and $V_R = 0{,}05$. For joints a slightly higher factor is used.

D.1.3. SPECIFIC DESIGN FORMULAS

Although a general formula is found, the actual formula differs for the different locations of the structure. This section shows the the design formulas per location based on Van Breukelen (2013).

CIRCUMFERENTIAL DIRECTION

For the circumferential direction hold the following formulas.

MID SECTION

As can be seen this formula differs slightly from the general formula given in equation (D.1).

$$\frac{R_t \cdot \gamma_r}{\gamma_{mat}} \geq y_{dyn} \cdot F_{stat} \tag{D.3}$$

DOWNSTREAM SIDE

$$\frac{R_t \cdot SCF_{test}}{\gamma_{mat}} \geq y_{dyn} \cdot SCF \cdot F_{stat} \tag{D.4}$$

UPSTREAM SIDE

$$\frac{R_t \cdot SCF_{test}}{\gamma_{mat}} \geq y_{dyn} \cdot SCF \cdot F_{stat} \tag{D.5}$$

JOINTS

$$\frac{R_t \cdot SCF_{test}}{\gamma_{mat}} \geq y_{dyn} \cdot SCF \cdot F_{stat} \tag{D.6}$$

LONGITUDINAL DIRECTION

For the longitudinal direction just one design criterion has been determined (Bouwdienst Rijkswaterstaat, 2007), it slightly differs from equation (D.1):

$$\frac{R_t \cdot SCF_{test}}{\gamma_{mat}} \geq y_{dyn} \cdot F_{stat,slope} \tag{D.7}$$

D.2. CHARACTERISTIC AND DESIGN FORCE AND STRENGTH

D.2.1. CIRCUMFERENTIAL DIRECTION

RAMSPOL

The characteristic tensile strength for the different locations follows from Van Breukelen (2013). These are strengths which already take relaxation, ageing and fatigue into account. The initial dry tensile strength of the membrane is 1870 kN/m. The static characteristic load follows from the calculations done in section 4.4.

	Middle section	**Downstream side**	**Upstream side**	**Joints**
R_t (kN)	960	970	970	892
F_{stat} (kN)	230,7	230,7	230,7	190[1]

Table D.2: Characteristic strength and force for Ramspol barrier (circumferential direction) (based on Van Breukelen (2013))

By using the parameters from table D.2 and the formulas from appendix D.1.3 the following results can be found:

	Middle section	**Downstream side**	**Upstream side**	**Joints**
R_d (kN)	840	1091	1091	947
F_d (kN)	299	966	1091	902
R_d/F_d	2,81	1,13	1,00	1,05

Table D.3: Design strength and force for Ramspol barrier (circumferential direction)

HARTEL LOCATION

For the Hartel location the same strength parameters for the membrane are used because the same membrane will be used. The static force can be found in table 4.8.

	Middle section	**Downstream side**	**Upstream side**	**Joints**
R_t (kN)	960	970	970	892
$F_{stat}(kN)$	151,5	151,5	151,5	125,2[2]

Table D.4: Characteristic strength and force for inflatable Hartel barrier (circumferential direction) (based on van Breukelen (2013))

The results of the calculations for the Hartel location can be found in table D.5.

	Middle section	**Downstream side**	**Upstream side**	**Joints**
R_d (kN)	840	1091	1091	947
F_d (kN)	197	636	719	594
R_d/S_d	4,27	1,71	1,52	1,59

Table D.5: Design strength and force for inflatable Hartel barrier (circumferential direction)

[1] For joints a lower force can be taken into account (Bouwdienst Rijkswaterstaat, 2007, p. 17)

[2] Calculated as follows: $F_{stat} = \frac{190}{130,7} \cdot 151,5$, based on the allowed decrease in force for the Ramspol barrier

D.2.2. LONGITUDINAL DIRECTION

For the longitudinal direction it has been determined that the strength is about one third of the strength in circumferential direction. Furthermore, a static force of 260 kN has been found for the Ramspol barrier by making use of the program MARC. The ξ factor from section 4.3.1 proved to be pretty accurate and for that reason this factor is also used to calculate the force for the Hartel location. This gives:

$$F_{\text{stat,slope}}(\text{Hartel}) = \xi \cdot F_{\text{stat,slope}}(\text{Ramspol}) = 0.57 \cdot 260 \approx 148 \ \text{kN/m} \tag{D.8}$$

The calculated forces and strength are given by table D.6.

	Ramspol	Hartel
R_d (kN)	343[3]	343
$F_{stat,slope}$ (kN)	260	148
F_d (kN)	338	192,4
R_d/F_d	1,02	1,78

Table D.6: Design strength and force for inflatable Hartel barrier (longitudinal direction)

[3] Approximated as follows: $R_d = \frac{1}{3} \cdot R_{t,upstream} \cdot SCF_{test} \cdot \gamma_{dyn}$

E

Checking the strength of the membrane for overflow

In section 4.2.2 is discussed that for design purposes the outside water level was assumed to be lower than the actual design water level. This appendix will discuss the consequences of the real pressures and forces working on the barrier. The maximum tensile force in the membrane should be about 230 kN/m, which is the tensile force for Ramspol.

E.1. Forces working on an overflowing (weir like) inflatable barrier

This section will discuss the situation of an inflatable barrier with a crest height of 9,5 m and an outside water level of 13,2 m. This will, next to increased water pressures, obviously result in overflow. This overflow is not taken into account although it will influence the design as well. For now only the static pressures are discussed.

Figure E.1 gives an impression of what the situation may look like in a 2-D cross section. It can be seen that the outside water level is 13,2 m and the part of the pressure working on the barrier is shown in black. This is a combination of a rectangle and a triangle. The pressures and forces for this side can be found in table E.1.

The inside water level is not as clear as the outside water level; water flows over the barrier and at some distance from the barrier the water level will be 7,7 m. However, it seems reasonable to assume that the water level just downstream of the barrier is higher than 7,7 m (as can be seen from figure E.1).

A good way of getting a first estimation of the tensile force in the membrane is to take the resultant of the forces due to static pressures. By doing this it is possible to determine what the minimum downstream water level should be to end up with a resultant force of about 230 kN/m, which is assumed to be equivalent to the tensile force in the membrane. It turns out that the downstream water level should be 1,25 m higher than the crest level of the bellow, which is 3,05 m higher than 7,7 m. If this is the case the resultant force is equal to 230 kN/m. It is believed that assuming that this relatively high inside water level is the case would be very optimistic.

	Assumed	Actual	Unit
$p_{b,1}$	129,5	129,5	kN/m^2
$p_{e,1}$	0	36,3	kN/m^2
$F_{total,1}$	442,7	787,5	kN/m

Table E.1: Assumed (table 4.3) and actual water pressures and forces due to the outside water level for the Hartel location

	Assumed	Actual	Unit
$p_{b,2}$	75,5	?	kN/m^2
$F_{total,2}$	290,8	?	kN/m
$F_{total,2}$	290,8	?	kN/m

Table E.2: Assumed (table 4.3) and actual water pressures and forces due to the inside water level for the Hartel location

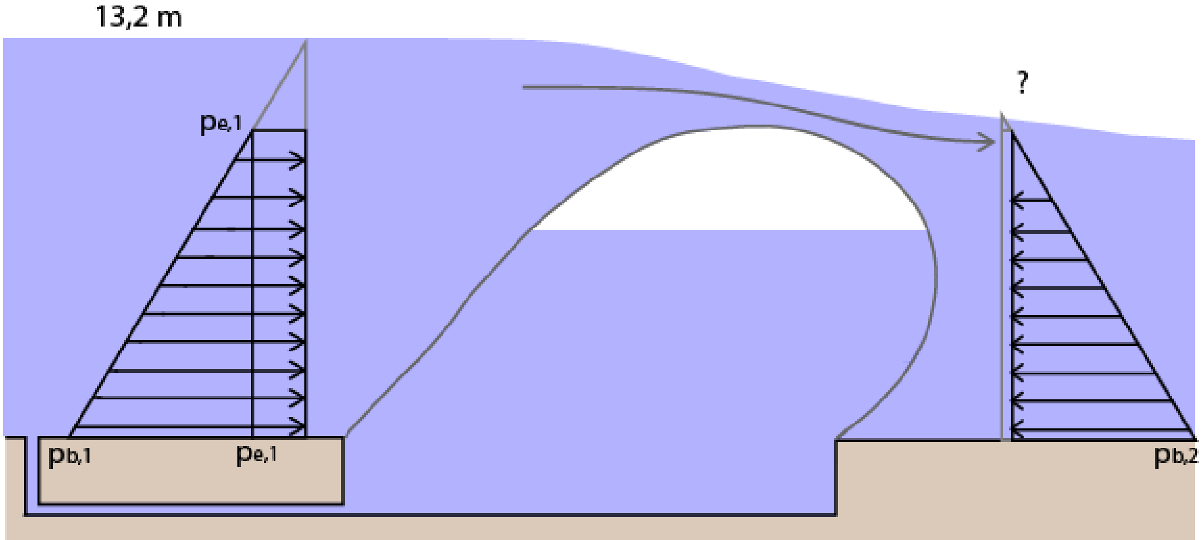

Figure E.1: Location and direction of forces for inflated barrier

From this short analysis can be concluded that it is likely that the tensile force in the membrane will be higher than 230 kN/m and for that reason a stronger membrane is required.

E.2. FORCES WORKING ON A FULL INFLATABLE BARRIER

Another method that is used to check the tensile force in the membrane for the real water levels will be discussed in this section. During this analysis it has been assumed that a barrier will be designed that does not allow overflow during design conditions. This means that the crest height of the barrier should be 13,2 m or higher (see figure E.2). By assuming this the spreadsheet created by Dirkmaat can be used. The results for inside water levels (h_2) of 7,7 and 9,5 m can be seen in tables E.3 and E.4.

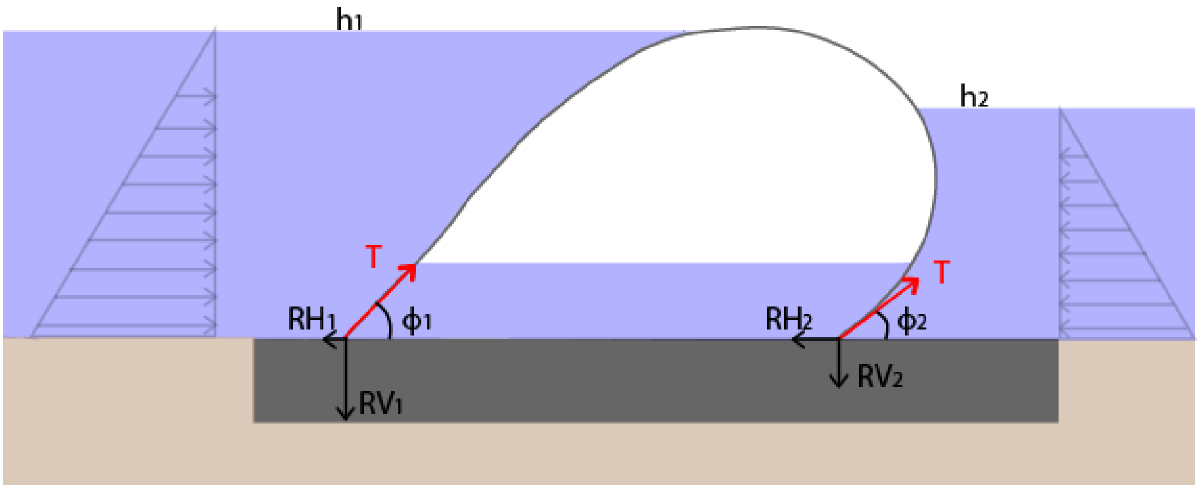

Figure E.2: Location and direction of forces for inflated barrier

From tables E.3 and E.4 can be seen that it is possible to design a barrier for an inside water level of 9,5 m and end up with a tensile force of about 230 kN/m. However, it can also be seen that is is impossible to design an inflatable barrier with a maximum tensile force of 230 kN/m for an inside water level of 7,7 m. Again the actual inside water level is of vital importance.

			Unit
h_1	13,2	13,2	m
h_2	**9,5**	**9,5**	m
head	3,7	3,7	m
h_{crest}	13,26	13,38	m
p_{air}	**0,3**	**0,25**	bar
h_{in}	10,2	10,7	m
RH_1	172,4	164,7	kN
RV_1	166,8	153,5	kN
RH_2	218,2	222,2	kN
RV_2	99,6	36,1	kN
T	**239,8**	**225,16**	kN
ϕ_1	44,1	43	degree
ϕ_2	24,5	9,2	degree

Table E.3: Results from the spreadsheet for an inside water level of 9,5 m and two different air pressures

			Unit
h_1	13,2	13,2	m
h_2	**7,7**	**7,7**	m
head	5,5	5,5	m
h_{crest}	13,29	13,22	m
p_{air}	**0,5**	**0,4**	bar
h_{in}	8,2	9,2	m
RH_1	259	235,3	kN
RV_1	294	234	kN
RH_2	298,5	311,7	kN
RV_2	253,7	113,8	kN
T	**391,8**	**331,8**	kN
ϕ_1	48,6	44,8	degree
ϕ_2	40,4	20,1	degree

Table E.4: Results from the spreadsheet for an inside water level of 7,7 m and two different air pressures

E.3. LOWER TENSILE FORCE FOR INFLATABLE HARTEL BARRIER

In chapter 4 a design of the barrier was sought with the lowest membrane length. The reason is that it is assumed that the main cost driver for the membrane is the membrane length. However, if the most important design parameter is the tensile force in the membrane it is possible to reduce this force significantly. This is shown in table E.5.

	Option 1	Option 2	unit
B_b	16	16	m
L	29	33,5	m
h_{in}	7,5	8,5	m
p_{air}	0,2	0,1	bar
h_{crest}	9,5	9,5	m
h_1	9,5	9,5	m
h_2	7,7	7,7	m
ϕ_1	0,82	0,03	rad
T	**103,15**	**79,47**	kN

Table E.5: Results from the spreadsheet for a lower tensile force for inflatable Hartel barrier

It can be seen that a reduction of more than 33% can be achieved by lowering the air pressure. A negative result of this action is that the membrane length increases.

E.4. EVALUATION OF THE USED MEMBRANE STRENGTH

From the above sections can be concluded that it is not completely sure if the membrane that was used for the Ramspol barrier will be sufficiently strong when used for the inflatable Hartel barrier. This chapter gave a short analysis of the possibilities. Possibly additional or stronger circumferential reinforcement is required. This will slightly increase the thickness of the membrane[1].

Another aspect is the significant wave height which will be significantly lower[2] for the Hartel barrier than for the Ramspol location (see table 4.2). And almost all of the wave will flow over the bellow in stead of hitting it because of the overflow. This will reduce the load on the barrier and can lead to the use of a (much) lower dynamic coefficient γ_{dyn}. So although the static pressures increase the dynamic effects decrease and that

[1] It will probably not be a very large increase since a large part(about 30%) of the thickness is due to the cover layers which will remain the same.

[2] More than a factor four

makes it difficult to determine the ultimate tensile force in the membrane.

Because it is not within the scope of this thesis and because it is very preferable to use the 'Ramspol membrane' (since cost information is available) this will not be investigated further. This is obviously something that should be further investigated if it is wished for to build an inflatable barrier at the Hartel location.

F

SOIL CONDITIONS

In chapter 6 the construction costs for the inflatable Hartel barrier are discussed. The costs for the foundation are based on the total force that is transferred to the subsoil by the foundation. This is only reasonable if the soil conditions are similar for both locations. Within this appendix will be shown that it seems reasonable to assume that the soil conditions are similar.

F.1. SOIL CONDITIONS IN THE NETHERLANDS IN GENERAL

Figures F.1 and F.2 show the global soil conditions in the Netherlands. For both locations can be seen that the soil consists mainly of clay. This strengthens the feeling that it is reasonable to base the costs for the inflatable Hartel barrier solely on the total force that has to be transferred.

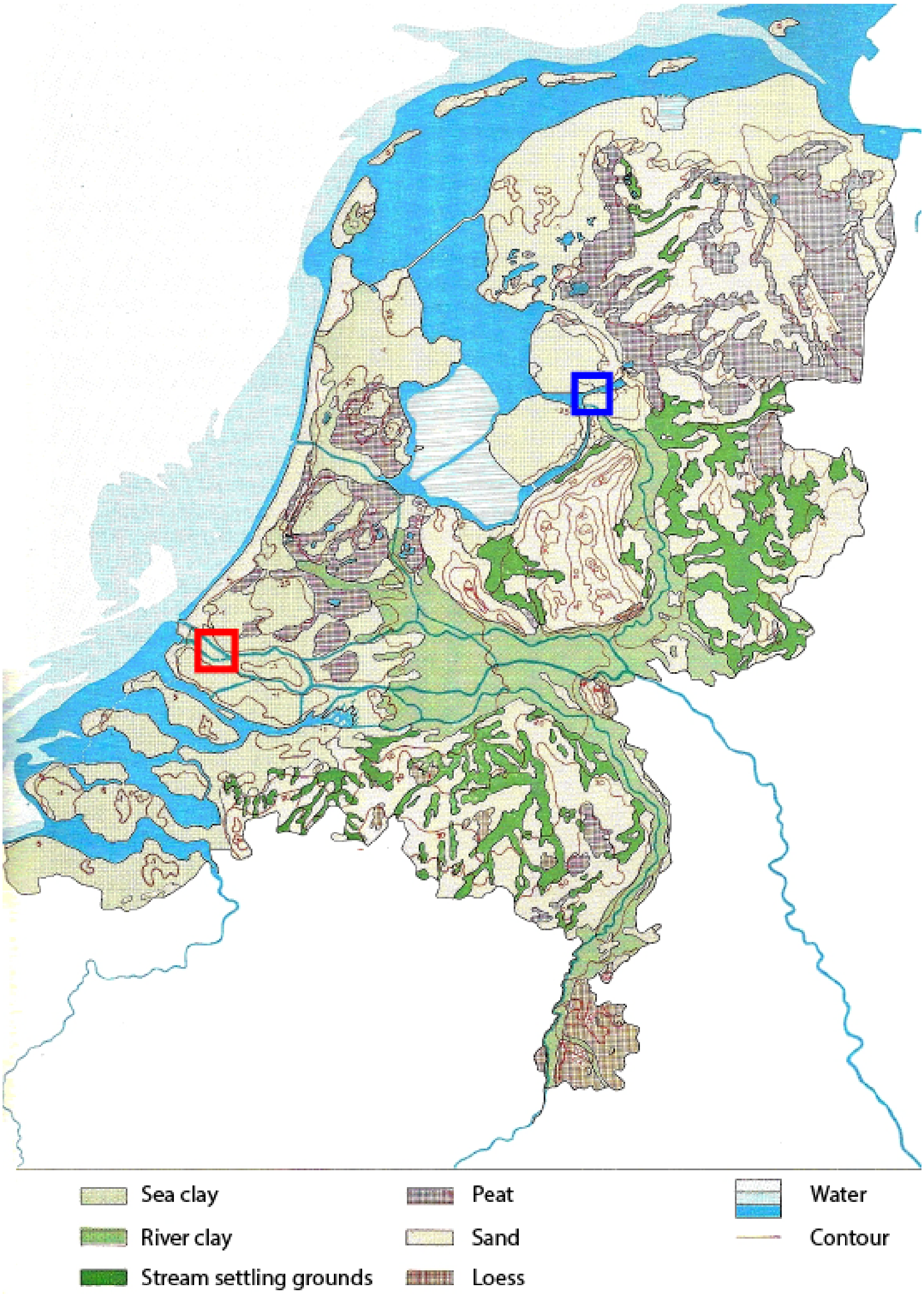

Figure F.1: Soil conditions in the Netherlands, the red square shows the location of the Hartel barrier and the blue square shows the location of the Ramspol barrier (based on Kamphuis (n.d.))

Figure F.2: Soil conditions in the Netherlands, the red square shows the location of the Hartel barrier and the blue square shows the location of the Ramspol barrier (based on Freese (2006))

F.2. SOIL CONDITIONS FOR THE SPECIFIC BARRIER LOCATIONS

Figure F.3 shows the soil conditions in the Netherlands. Furthermore, the Netherlands has been divided into squares, which are sub-maps with more detailed information for that location. The two red squares are the locations of the barriers. Part of the detailed sub-maps can be seen in figures F.4 and F.5. It can be seen that the soil for both locations predominantly consists of clay. However, at the Ramspol location (figure F.5) shows also sand and loess. It has been assumed that the superabundance of clay is governing and this is the same for both locations. From this can be concluded that the soil conditions are comparable.

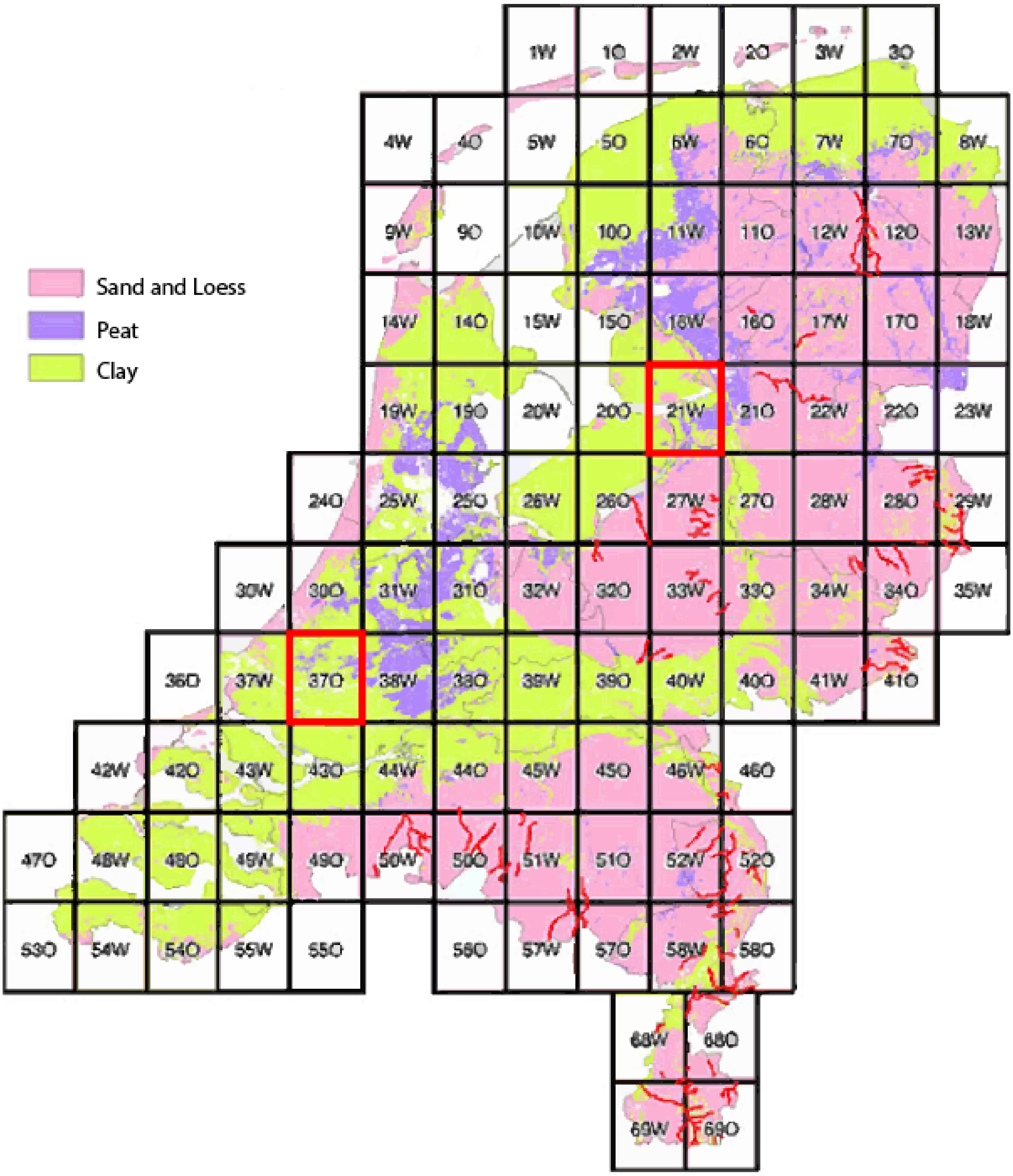

Figure F.3: Soil conditions in the Netherlands and division in more detailed sub-maps, in red the maps used for more detailed information (37O and 21W) (based on Alterra Wagening UR (2005))

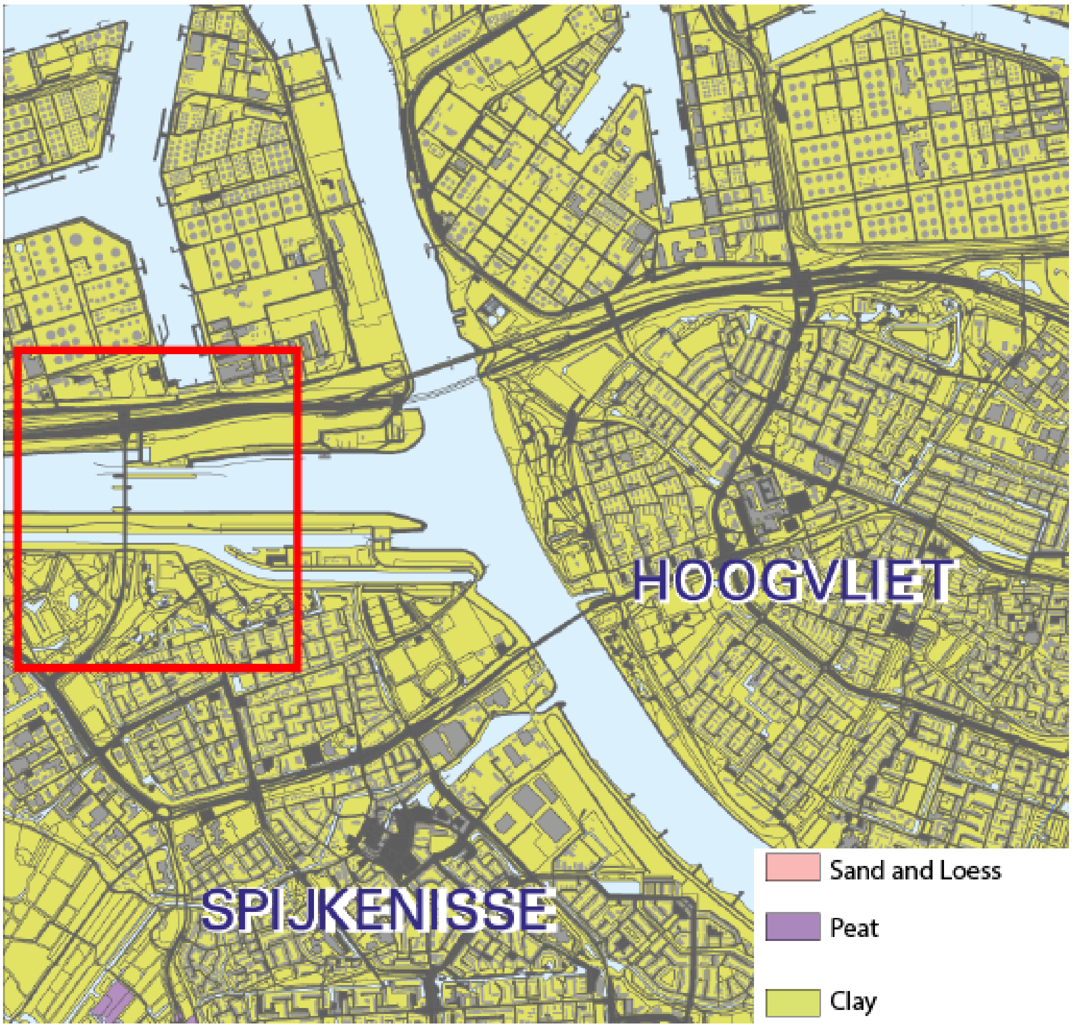

Figure F.4: Soil conditions for the Hartel location, the red square gives the location of the barrier (based on Alterra Wageningen UR (2008))

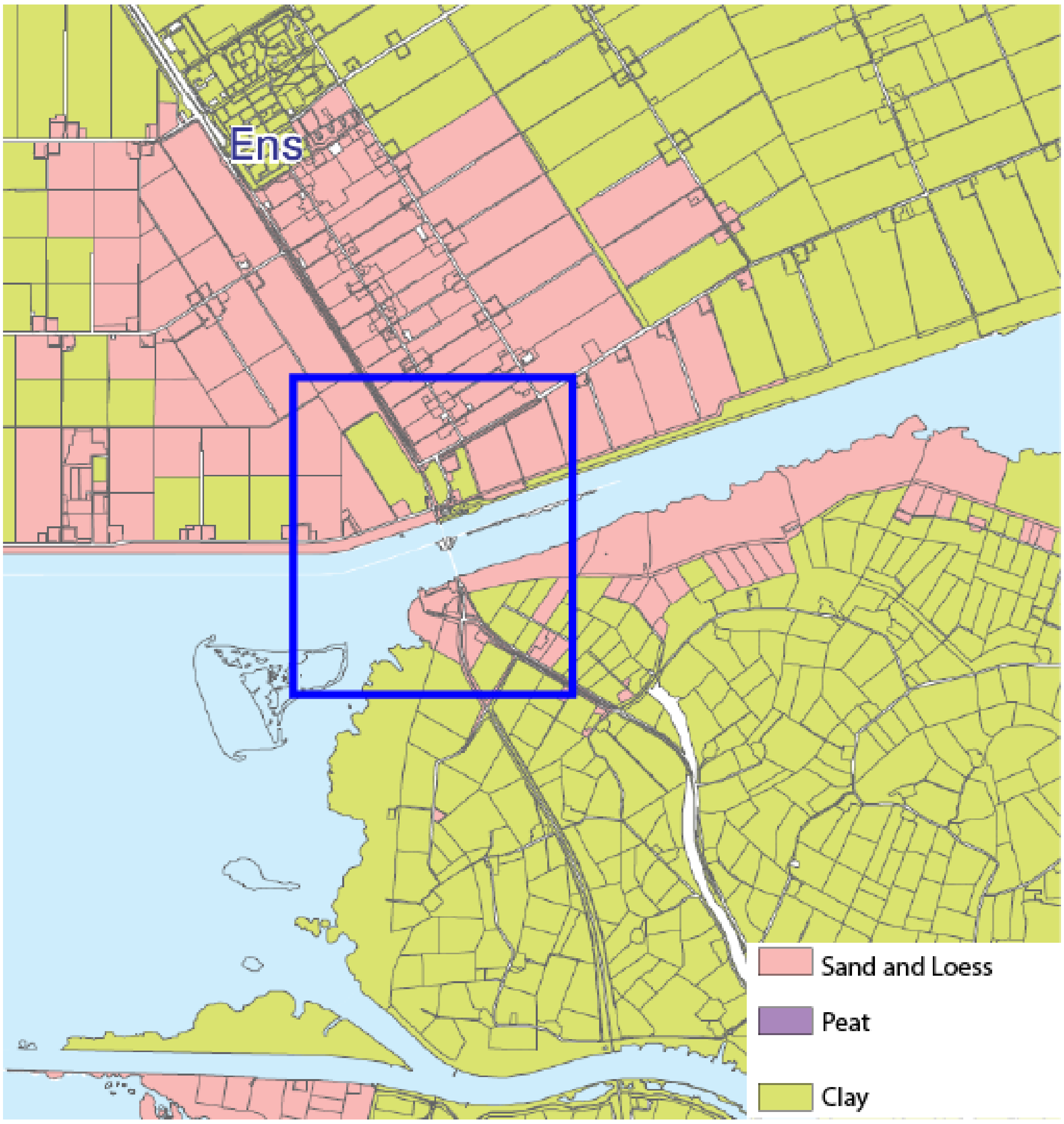

Figure F.5: Soil conditions for the Ramspol location, the blue square gives the location of the barrier (based on Alterra Wagening UR (2013))

G

GROUNDWORK

Figure G.1 shows the groundwork that had to be done for the Ramspol barrier. In blue the work on the adjacent levees, in green the in between abutment, in yellow the divider for Ramsgeul and Ramsdiep and in red on of the dump pits for excavated soil.

Figure G.1: Groundwork for the Ramspol barrier

H

CONSTRUCTION COSTS BED PROTECTION ORIGINAL HARTEL BARRIER

According to Boer (1993) the construction costs of the bed protection for the original Hartel barrier were estimated to be about 12 million guilder in 1993. Based on this the costs for constructing the same bed protection at relevant moments are calculated. For this calculation a fixed discount rate of 2,5% has been used (see section 2.4). The costs are rounded to 100.000.

Bed protection original Hartel		
Bed protection 1993	12.000.000	guilder
Bed protection 1996	12.900.000	guilder
Bed protection 1996	5.900.000	euro
Bed protection 1997	13.200.000	guilder
Bed protection 1997	6.000.000	euro
Bed protection 2014	9.100.000	euro

Table H.1: Construction costs bed protection original Hartel barrier at relevant moments

I

STATISTICAL INFORMATION MONTE CARLO SIMULATION

I.1. HARTEL

Figures I.2 and I.2 show the results of the Monte Carlo simulation for the Hartel barrier in a histogram and cumulative distribution function (cdf). They also give the normal distribution that is used for the cost levels with a 5% and 95% confidence level. It can be seen that the normal distributions match pretty well with the assumed distributions.

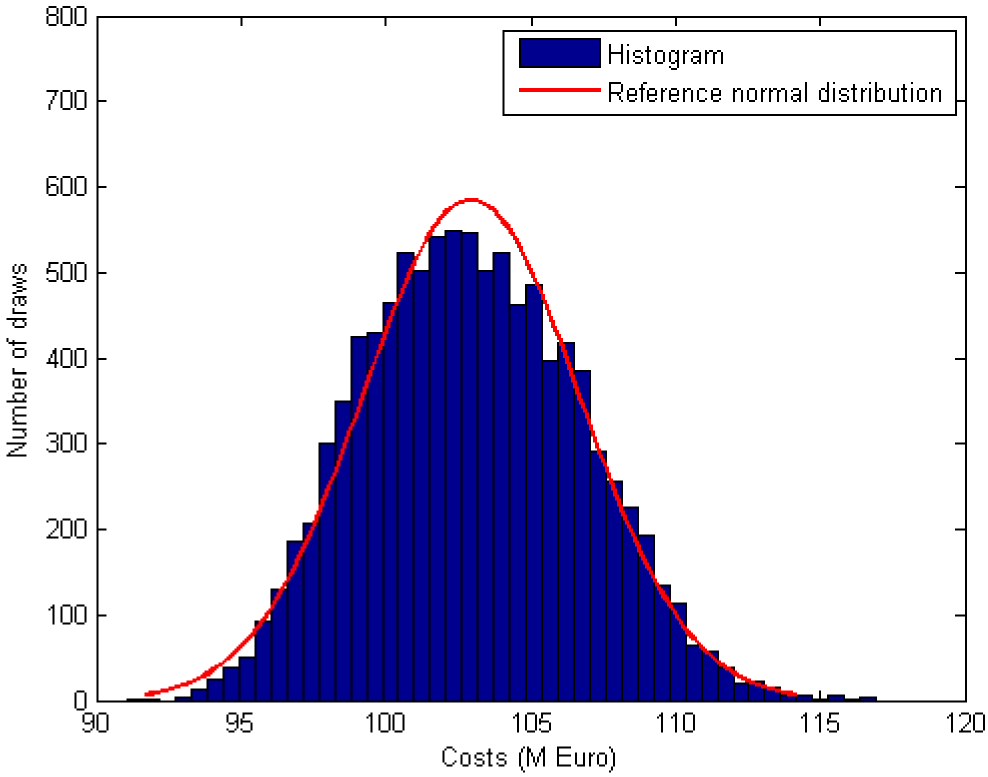

Figure I.1: Histogram for the Hartel barrier. In blue the histogram and in red the normal distribution that is used

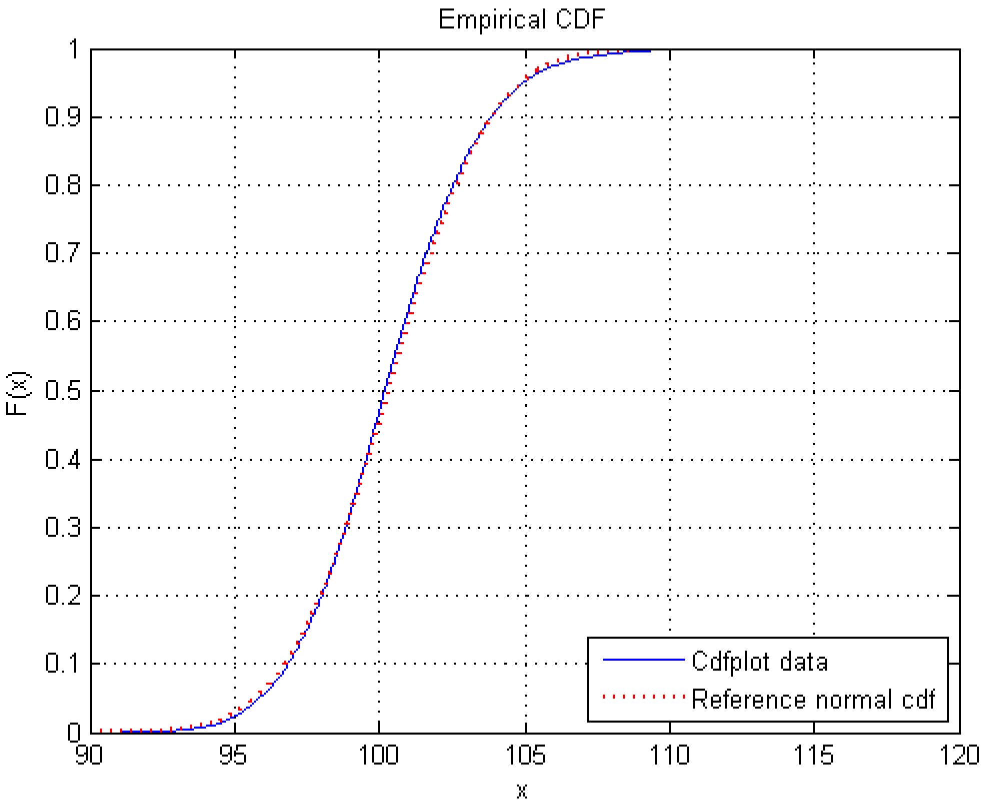

Figure I.2: CDF for the Hartel barrier. In blue the histogram and in red the normal distribution that is used

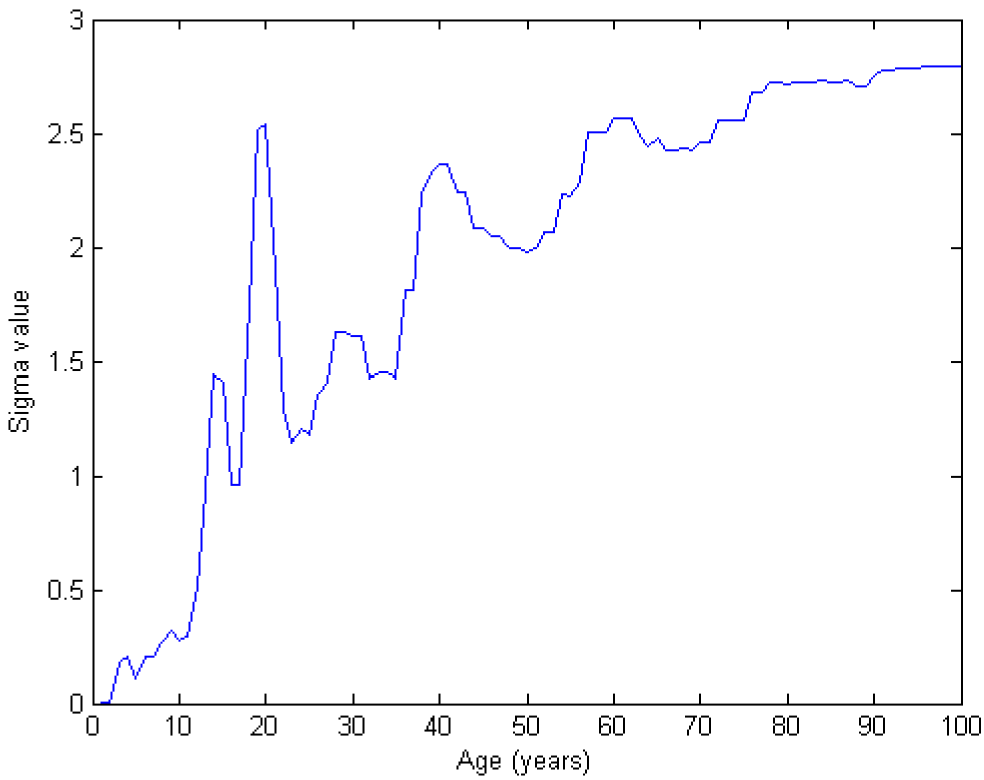

Figure I.3: Development of the standard deviation (sigma) for the Hartel barrier

I.2. INFLATABLE HARTEL

Figures I.2 and I.2 show the results of the Monte Carlo simulation for the inflatable Hartel barrier and the used normal distributions as reference. From both figures can be seen that the assumed normal distribution is reasonable.

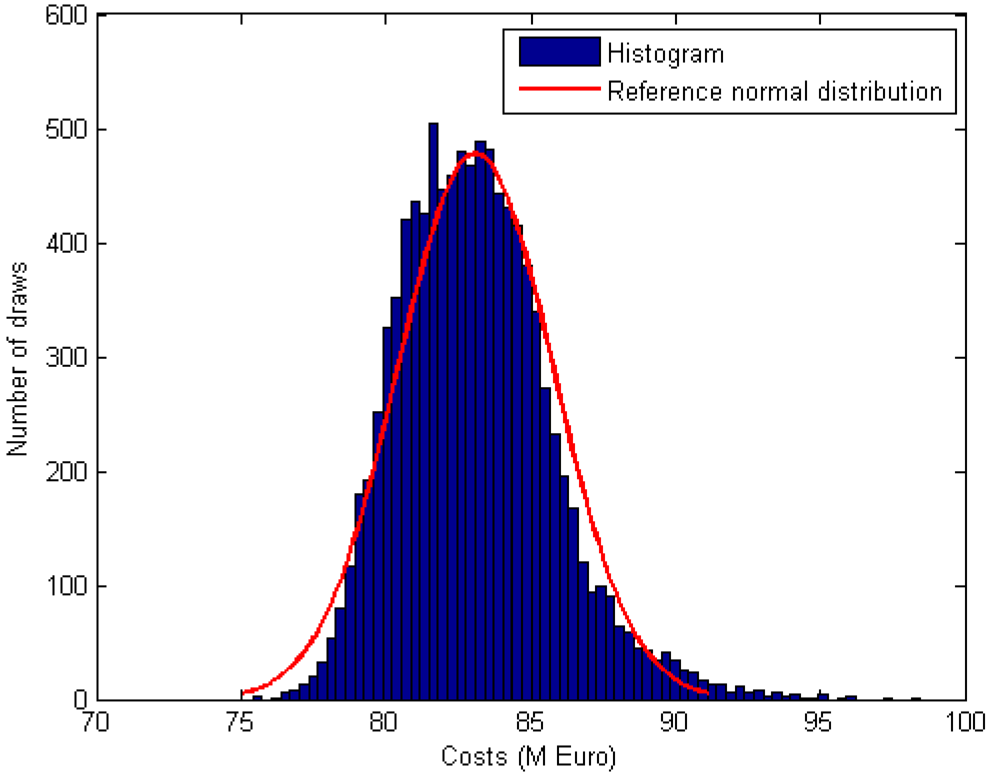

Figure I.4: Histogram for the inflatable Hartel barrier. In blue the histogram and in red the normal distribution that is used

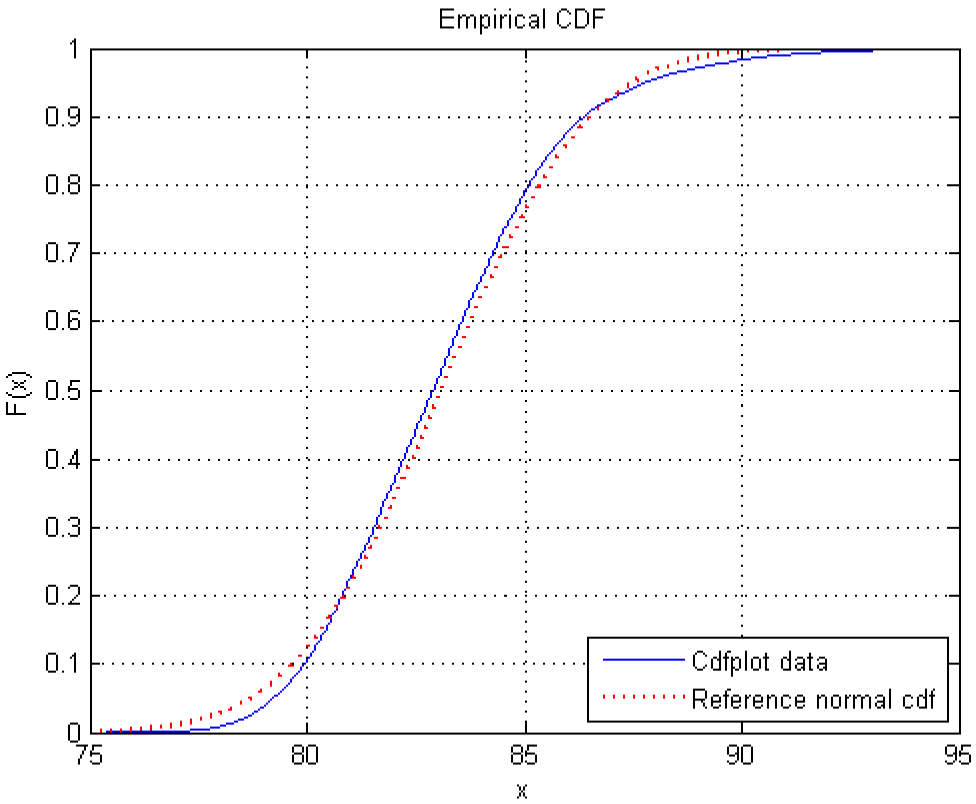

Figure I.5: CDF for the inflatable Hartel barrier. In blue the histogram and in red the normal distribution that is used

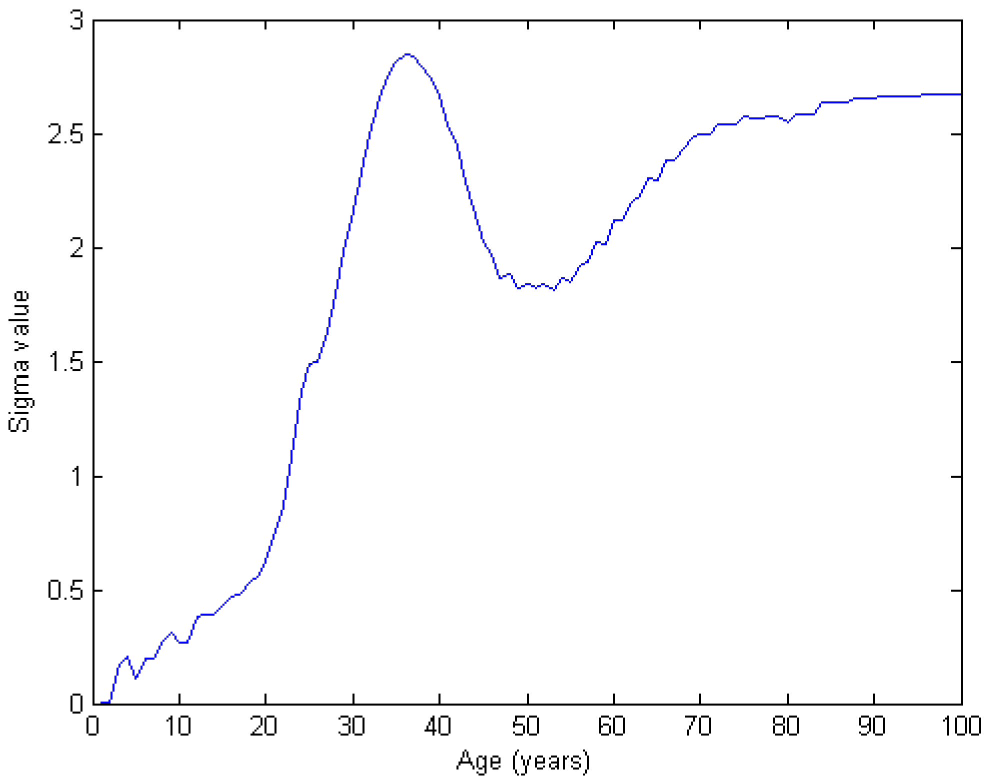

Figure I.6: Development of the standard deviation (sigma) for the inflatable Hartel barrier

I.3. SKEWED DISTRIBUTIONS

As can be seen from figures I.1 and I.4 and table 8.9 the distributions are slightly skewed and do no follow the normal distribution precisely. The reason is probably that the maintenance of the membrane and the doors slightly dominate. This has been investigated by changing the costs and lifetime for the membrane and using the same code. The result is a better fit for the normal distribution. Figure I.7 shows the histogram and the corresponding normal distribution for changed membrane parameters; replacement costs of 4 million, a standard deviation of 1,5 million, lifetime of 20 years with a standard deviation of 2 years.

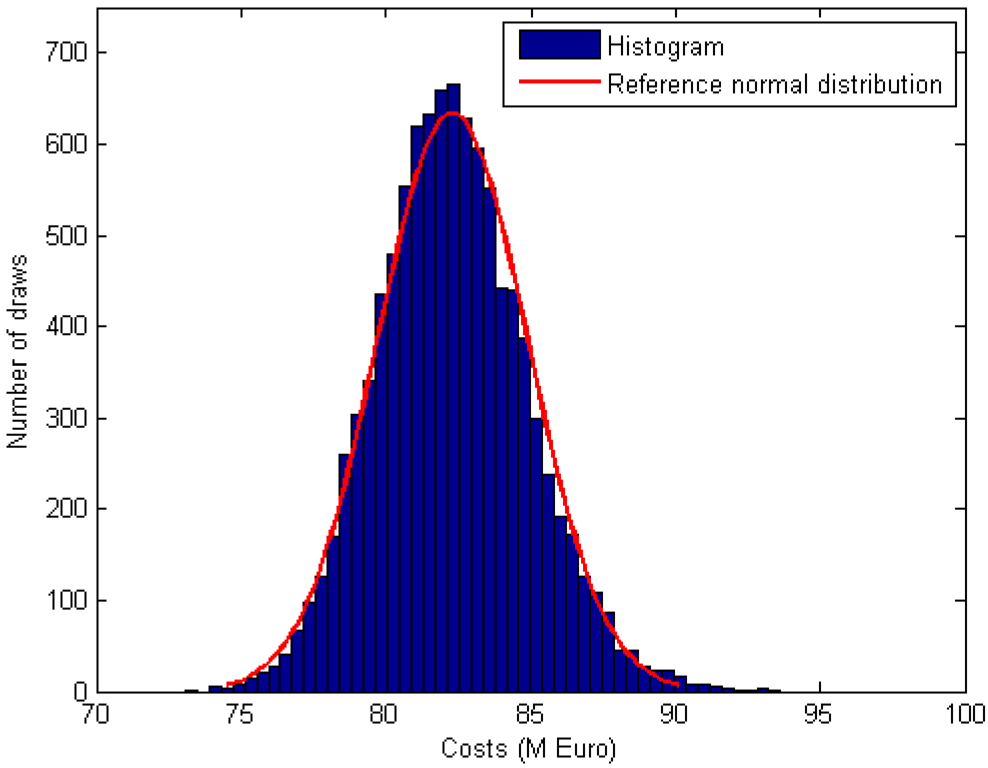

Figure I.7: Lower costs and lifetime for membrane result in better fit normal distribution

The dominance of the maintenance costs for the membrane, and to a lesser extent for the doors, result in this skewness.

J

Event tree Hartel barrier

The event tree for a storm and/or rain event for the (inflatable) Hartel barrier is given by figure J.1. Starting with a storm and/or rain event it shows the different things that can happen. A clarification for the different steps:

- **Storm/rain event:**
  This event tree starts with a storm and/or rain event, which may lead to extreme water levels.
- **Expected water level:**
  Due to the storm and/or rain event the expected water levels may be higher (>) or lower (<) than a certain threshold level. The barrier will close if the expected water level is higher than the threshold value and will stay open if it is expected to be lower.
- **Barries closes/does not close:**
  If the expected water level is higher than the threshold water level the barrier should close. It can happen that the barrier does not close although it should.
- **Actual water level:**
  Regardless of the expected water level, the actual water level may be higher (>) or lower (<) than the expected water level (e.g. in case of miscalculations). An actual water level which is lower than the threshold level results in a safe situation and the tree stops.
- **Load versus strength:**
  In case of a closed barrier the load, due to the storm and/or rain event, may be higher (>) or lower (<) than the strength of the barrier. In case of a higher load than strength the barrier fails if it is the other way around the barrier works and the event tree stops.
- **Flooding:**
  When the barrier fails (e.g. in case of load>strength) in combination with an actual water level which is higher than the threshold level a flooding will occur. Depending on the event a small or an extreme flooding will occur.

The failure probabilities for both the Ramspol barrier and the Hartel barrier are given by table J.1.

	Hartel[1]	Ramspol[2]	Unit
Structural failure during total life	10^{-5}	10^{-5}	per year
Exceedance frequency water levels	10^{-4}	$1{,}4 \cdot 10^{-4}$	per year
Total failure probability	10^{-3}	$3{,}5 \cdot 10^{-3}$	per event

Table J.1: Failure probabilities Ramspol and Hartel barriers

[1] According to Van der Burgh et al. (1998)
[2] According to Bouwdienst Rijkswaterstaat (2007)

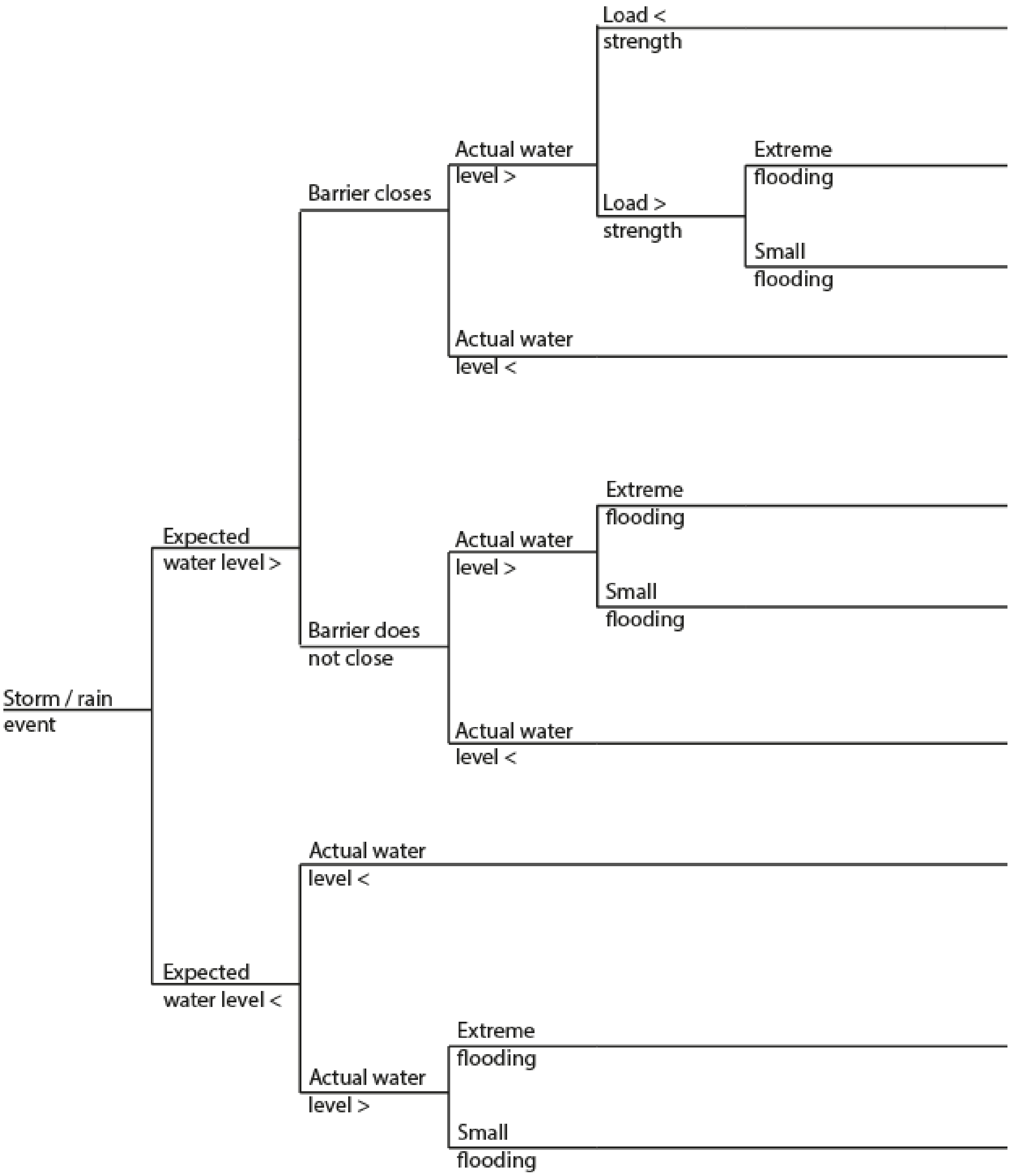

Figure J.1: Event tree for a storm and/or rain event for the (Inflatable) Hartel barrier

K

MONTE CARLO SIMULATION MATLAB CODE

This section give the Matlab code for the Monte Carlo simulation for the Hartel barrier that has been used in chapter 8.

```
clear; close all;

%% Start calculation time
tic;
initime = cputime;
time1   = clock;

%% Chose number of draws, discount rate, etc.

n=10000;  %number of draws for MC simulation
maxage=100; %life of asset (100 years)
dr=0.025; %Discount rate = 2.5 %
time = linspace(1,maxage,maxage); %Time per year (necessary for plot x-axis)
Harteldata=xlsread('InputLCC.xlsx', 'Hartel', 'B3:E12'); %loading the input data
p=rand(n,6); %Drawing random probabilities of underestimating for each variable

%% Increase calculation speed
CI=zeros(n,maxage);
CM=zeros(n,maxage);
COS=zeros(n,maxage);
yearlymaintenance=zeros(n,maxage);
yearlymaintenance2=zeros(n,maxage);
C20=zeros(1,maxage);
C25=zeros(1,maxage);
C50=zeros(1,maxage);
LTInstallations=zeros(1,n);
LTMembrane=zeros(1,n);
LTOS=zeros(1,n);
NROS=zeros(1,n);
NRi=zeros(1,n);
NRm=zeros(1,n);
mr20=zeros(1,4);
mr25=zeros(1,3);
mrm=zeros(6,n);
mri=zeros(6,n);
mros=zeros(50,n);
cumulativemaintenance=zeros(n,maxage);
cumulativemaintenance2=zeros(n,maxage);
EACy=zeros(n,maxage);
EACy2=zeros(n,maxage);

%% Maintenance costs
MCMembrane=norminv(p(:,1),Harteldata(2,1),Harteldata(2,2)); %Calculating the construction costs
%for the Membrane
MCInstallations=norminv(p(:,2),Harteldata(3,1),Harteldata(3,2)); %Calculating the construction costs
%for the CS
```

```
MCOS=norminv(p(:,3),Harteldata(4,1),Harteldata(4,2)); %Calculating the construction costs
%for the OS
Abut=Harteldata(5,1); %assigning costs for Abutment maintenance
Ships=Harteldata(6,1); %assigning costs for Guidance works maintenance
Office=Harteldata(7,1); %assigning costs for Office maintenance
Found=Harteldata(8,1); %assigning costs for Foundation maintenance
Bbp=Harteldata(9,1); %assigning costs for Bed protection maintenance
GW=Harteldata(10,1); %assigning costs for Groundwork maintenance
Ctot20=Found(1)+GW(1)+Abut(1)+Bbp(1); %Calculating costs with a reoccurance time of 20 years
mr50=50; %Moments to replace part with LT of 50 years

for i=1:1:4
    mr20(i)=20*i; %Moments to replace part with LT of 20 years
end
for i=1:1:3
    mr25(i)=25*i; %Moments to replace part with LT of 25 years
end

for i=1:1:n
    LTMembrane(i)=round(norminv(p(i,4),Harteldata(2,3),Harteldata(2,4)));
    NRm(i)=(floor((maxage-1/2*LTMembrane(i))/LTMembrane(i)));
    for s=1:1:NRm(i)
        mrm(s,i)=LTMembrane(i)*s; %Moments to replace membrane
    end


LTInstallations(i)=round(norminv(p(i,5),Harteldata(3,3),Harteldata(3,4)));
    NRi(i)=(floor((maxage-1/2*LTInstallations(i))/LTInstallations(i)));
    for s=1:1:NRi(i)
        mri(s,i)=LTInstallations(i)*s; %Moments to replace cs
    end


LTOS(i)=round(norminv(p(i,5),Harteldata(4,3),Harteldata(4,4)));
NROS(i)=(floor((maxage-1/2*LTOS(i))/LTOS(i)));
    for s=1:1:NROS(i)
        mros(s,i)=LTOS(i)*s; %Moments to replace os
    end
end

for i=1:1:n
for j=1:1:maxage
   if ismember(j,mros(:,i)) %Costs for replacement OS in millions at the moments they occur
        COS(i,j) = MCOS(i)/(1+dr)^(j);
   else
        COS(i,j) = 0;
   end

   if ismember(j,mri(:,i)) %Costs for replacemen t OS in millions at the moments they occur
        CI(i,j) = MCInstallations(i)/(1+dr)^(j);
   else
        CI(i,j) = 0;
   end

   if ismember(j,mrm(:,i)) %Costs for replacement OS in millions at the moments they occur
        CM(i,j) = MCMembrane(i)/(1+dr)^(j);
   else
        CM(i,j) = 0;
   end

   if ismember(j,mr20) %Costs for replacement OS in millions at the moments they occur
        C20(j) = Ctot20/(1+dr)^(j);
   else
        C20(j) = 0;
   end

   if ismember(j,mr50) %Costs for replacement OS in millions at the moments they occur
        C50(j) = Office(1)/(1+dr)^(j);
   else
        C50(j) = 0;
   end
```

```
    if ismember(j,mr25) %Costs for replacement OS in millions at the moments they occur
        C25(j) = Ships(1)/(1+dr)^(j);
    else
        C25(j) = 0;
    end

    yearlymaintenance(i,j)=COS(i,j)+CM(i,j)+CI(i,j)+C20(j)+C25(j)+C50(j); %All costs that occur
    %during lifetime
    yearlymaintenance2(i,j)=yearlymaintenance(i,j); %Copy of yearlymaintenance
    yearlymaintenance(i,1)=yearlymaintenance(i,1)+Harteldata(1,1); %Include construction costs
    %in year 1

    if j==1 %Cumulative costs for maintenance in millions including construction costs
        cumulativemaintenance(i,j)=yearlymaintenance(i,j);
    else
        cumulativemaintenance(i,j)=yearlymaintenance(i,j)+cumulativemaintenance(i,j-1);
    end


    if j==1 %Cumulative costs for maintenance in millions without construction costs
        cumulativemaintenance2(i,j)=yearlymaintenance2(i,j);
    else
        cumulativemaintenance2(i,j)=yearlymaintenance2(i,j)+cumulativemaintenance2(i,j-1);
    end

end
end

%% Expected Annual Costs and mean costs
final=cumulativemaintenance(:,100); %Assigning NPV to final
EAC=final/maxage; %Calculate EAC including Construction costs
EAC2=cumulativemaintenance2(:,100)/maxage; %Calculate EAC without Construction costs

for i=1:1:n %Cumulative EAC including Construction costs
for j=1:1:maxage
    EACy(i,j)=EAC(i)*j;
end
end

for i=1:1:n %Cumulative EAC without Construction costs
for j=1:1:maxage
    EACy2(i,j)=EAC2(i)*j+Harteldata(1,1);
end
end

%% Probabilistics

EACm=sum(EACy)/n; %Mean EAC
final2=EACy(:,100); %Assigning NPV to final (shoudl be same as final)
[mu,sigma]=normfit(EACy2); %Find mu and sigma for normal distribution EAC without CC
[mu2,sigma2]=normfit(cumulativemaintenance); %Find mu and sigma for normal distribution
%cumulative maintenance
hoog=norminv(0.95,mu,sigma); %Prob. of underestimating of 95%
hoog(isnan(hoog))=0; %Assigning 0 if NaN is detected
mid=norminv(0.5,mu,sigma); %Prob. of underestimating of 50%
mid(isnan(mid))=0; %Assigning 0 if NaN is detected
laag=norminv(0.05,mu,sigma); %Prob. of underestimating of 5%
laag(isnan(laag))=0; %Assigning 0 if NaN is detected

hoog2=norminv(0.95,mu2,sigma2); %Prob. of underestimating of 95%
hoog2(isnan(hoog))=0; %Assigning 0 if NaN is detected
mid2=norminv(0.5,mu2,sigma2); %Prob. of underestimating of 50%
mid2(isnan(mid))=0; %Assigning 0 if NaN is detected
laag2=norminv(0.05,mu2,sigma2); %Prob. of underestimating of 5%
laag2(isnan(laag))=0; %Assigning 0 if NaN is detected

%% Plots

figure(1)
plot(time,laag,':',time,mid,time,hoog,'--')
```

```
legend('5%','50%','95%','Location','SouthEast')
%title('Probability of underestimating')
xlabel('Age (years)')
ylabel('Costs (M Euro)')
axis([0 100 0 120])

figure(4)
plot(time,laag2,':',time,mid2,time,hoog2,'--')
legend('5%','50%','95%','Location','SouthEast')
%title('Probability of underestimating')
xlabel('Age (years)')
ylabel('Costs (M Euro)')
axis([0 100 0 120])

figure(2)
cdfplot(final2)
hold on
x=90:0.1:120;
f=normcdf(x,mu(100),sigma(100));
plot(x,f,'r:','LineWidth',2)
legend('Cdfplot data','Reference normal cdf','Location','SouthEast')

figure(3)
histfit(final,50,'normal')
axis([90 120 0 800])
legend('Histogram','Reference normal distribution','Location','NorthEast')
xlabel('Costs (M Euro)')
ylabel('Number of draws')

figure(5)
plot(time,sigma2)
xlabel('Age (years)')
ylabel('Sigma value')

%% Print calculation time

fintime = cputime;
elapsed = toc;
time2   = clock;
fprintf('TIC TOC: %g\n', elapsed);
fprintf('CPUTIME: %g\n', fintime - initime);
fprintf('CLOCK:   %g\n', etime(time2, time1));
```

TRADEMARKS

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References

Alterra Wagening UR. (2005, December). *Overzichtskaart bij het uitvoeringsbesluit meststoffenwet.* Retrieved from http://www2.hetlnvloket.nl/mijndossier/grondsoortenkaart/GRONDSOORTEN_files/OVERZICHTSKAART-GRONDSOORTEN.JPG

Alterra Wagening UR. (2013, Januay). *Bijlage i (behorende bij artikel 3 van het uitvoeringsbesluit).* Retrieved from http://www2.hetlnvloket.nl/mijndossier/grondsoortenkaart/kaarten2013/grondsoortenkaart_21w.PDF (Commissioned by Ministerie van Economische Zaken)

Alterra Wageningen UR. (2008, April). *Bijlage i (behorende bij artikel 3 van het uitvoeringsbesluit).* Retrieved from http://www2.hetlnvloket.nl/mijndossier/grondsoortenkaart/kaarten2008/gronds08-37o.PDF (Commissioned by Ministerie van Landbouw, Natuur en Voedselkwaliteit)

Averkamp, H. (-). *What is capital budgeting?* Retrieved from http://www.accountingcoach.com/blog/what-is-capital-budgeting

Averkamp, H. (n.d.). *What is the difference between present value (pv) and net present value (npv)?* Retrieved from http://www.accountingcoach.com/blog/net-present-value

Beleidsnota waterkeringen. (2010, January). Retrieved from http://decentrale.regelgeving.overheid.nl/cvdr/XHTMLoutput/Historie/Waterschap%20Hollandse%20Delta/272885/272885_1.html

Bijl, I. W. (2006, October). *Achterlandstudie Maeslantkering* (Tech. Rep.). Rijkswaterstaat. Retrieved from https://zoek.officielebekendmakingen.nl/kst-30800-A-6-b1.pdf

Boer, P. (1993). *Bodemverdediging stormvloedkering Hartelkanaal* (Master's thesis, Delft University of Technology). Retrieved from http://repository.tudelft.nl/assets/uuid:5b5a0ee8-84e9-46c4-af79-e4216646e8da/Boer1993a.pdf

Bouwdienst Rijkswaterstaat. (2007, December). *Kennis- en ervaringsdocument balgkering Ramspol* (Tech. Rep. No. Registratienummer: WG-SE20071295). DHV voor Bouwdienst Rijkswaterstaat. (Dossier X3659.01.002)

BusinessDictionary.com. (n.d.). *Present value (pv).* Retrieved from http://www.businessdictionary.com/definition/present-value-PV.html

Cost Analysis Improvement Group. (1992, May). *Operating and support cost-estimating guide* (Guide). Department of Defense. Retrieved from http://www.dtic.mil/pae/index.html

DataMarket. (2012). *Interest rates, discount rate for euro area.* Retrieved from http://datamarket.com/data/set/1wfm/interest-rates-discount-rate-for-euro-area#!ds=1wfm&display=line&f=index (Provider source: International Monetary Fund)

Delta Marine Consultants (DMC). (2011). *Balgstuw Ramspol tijdens storm.* Retrieved from http://www.dmc.nl/upload/images/dmc/project_images/balgstuw-ramspol-3-1.jpg

de Pagter, I. J. C. (1996). Bouw van de Hartelkering. *CEMENT*, *5*, 8-12.

Det Norske Veritas AS (DNV). (2011, April). *Modelling and analysis of marine operations* (Tech. Rep. No. DNV-RP-H103). DNV. Retrieved from http://www.stalforbund.com/_member/rp-h103_2011-04.pdf

de Vries, P. A. L. (2014). *Bolivar Roads Surge Barrier, a conconcept design for the environmental section* (Master's thesis, Delft University of Technology). Retrieved from http://repository.tudelft.nl/view/ir/uuid%3A7ed299d4-4118-4f1f-a868-ec37b95dd2a0/

Dircke, P. T. M., Jongeling, T. H. G., & Jansen, P. L. M. (2012, April). Innovative dam and levee design and construction. In (Ed.), *Innovative Dam and Levee Design and Construction for Sustainable Water Management* (p. 65-87). USSD. (Proceedings to the 32nd annual USSD conference)

Dirkmaat, A. (2011). *Voorlopig ontwerp balgkering "Het Spui"* (Tech. Rep.). DHV & Hogeschool Utrecht.

Dorreman, J. (1997). *Balgstuw gevuld met lucht en/of water* (Master's thesis, Delft University of Technology). Retrieved from http://repository.tudelft.nl/search/ir/?q=dorreman&faculty=&department=&type=&year=

Durkee, D. B., Ackerman, A. F., & Schweiger, P. G. (2013). Reviewing refurbishment options for Tempe Town Lake dam, Arizona. *Hydropower & Dams*, *4*, 46 - 50.

Federal Reserve Bank of St. Louis (FRED). (2014, March). *Interest rates, discount rate for euro area.* Retrieved from http://research.stlouisfed.org/fred2/series/INTDSREZQ193N

Florida Department of Transportation (FDOT). (2014, April). *Bridge costs.* Retrieved from http://www.dot.state.fl.us/planning/policy/costs/Bridges.pdf

Freese, A. (2006). *Op wat voor grond tuinier je?* Retrieved from http://www.freewebs.com/belevenissen-van-een-tuinkabouter/Grondsoorten%20Nederland.jpg

Hartsuijker, C. (2001). *Spanningen, vervormingen, verplaatsingen* (Deel 2 ed.) (No. ISBN 90 395 0594 2). Academic Service, Sdu Uitgevers.

Horvat & Partners. (2010, -). *Onderzoek doekligging stormvloedkering ramspol.* Retrieved from http://www.horvat.nl/ons-werk/referentieprojecten/onderzoek-doekligging-stormvloedkering-ramspol-obv-testprogramma

I-Storm International Network. (-). *Hartelbarrier.* Retrieved from http://www.i-storm.org/international/storm-surge-barriers/barriers/hartelbarrier/

Intergovernmental Panel on Climate Change (IPCC). (2013). *Climate change 2013; the physical science basis* (Tech. Rep.). IPCC. Retrieved from http://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf

Investopedia. (-). *Equivalent annual cost - eac.* Retrieved from http://www.investopedia.com/terms/e/eac.asp

ir. K. Steenepoorte. (2014, October). *De stormvloedkering in de oosterschelde.* Retrieved from http://www.rijkswaterstaat.nl/water/veiligheid/bescherming_tegen_het_water/deltawerken/oosterscheldekering/index.aspx (Rijkswaterstaat)

ISO. (2008, June). *NEN-ISO 15686-5:2008,IDT Buildings and constructed assets - Service-life planning - Part 5: Life-cycle costing* [International Standard].

Jongeling, T. H. G. (2005, december). *Hydraulische aspecten van balgstuwen en balgkeringen* (Tech. Rep.). Bouwdienst Rijkswaterstaat WL | Delft Hydraulics. Retrieved from http://publicaties.minienm.nl/download-bijlage/16986/hydraulische-aspecten-van-balgstuwen-en-balgkeringen.pdf

Jonkman, S. N. (2007). *Loss of life estimation in fl ood risk assessment* (Doctoral dissertation, Delft University of Technology). Retrieved from http://repository.tudelft.nl/assets/uuid:bc4fb945-55ef-4079-a606-ac4fa8009426/ceg_jonkman_20070618.pdf

Kamphuis, H. (n.d.). *Basisprincipes voor een natuurlijke inrichting van ruimte.* Retrieved from http://www.hkamphuis.nl/uploads/images/bodem/Tweedenotabodem.jpg (Image from "Tweede Nota Ruimtelijke Ordening (1966)")

Kumar, U. D., Chattopadhyay, G., & Pannu, H. S. (2004). *Total cost of ownership for railway assets: A case study on boxn wagons of indian railways.* (Proceedings of the Fifth Asia Pacific Industrial Engineering and Management Systems Conference 2004)

Leidraad Kunstwerken. (2003, May). TAW. Retrieved from http://repository.tudelft.nl/assets/uuid:3a3aead8-08a8-4c99-afe9-ada2811d15c1/L15-Leidraad_kunstwerken.pdf

Linham, M. M., & Nicholls, R. J. (n.d.). *Storm surge barriers and closure dams.* Retrieved from http://www.climatetechwiki.org/content/storm-surge-barriers-and-closure-dams

Melisie, I. E. J. (2006, January). *Veiligheid nederland in kaart; risicocase dijkring 14 zuid-holland, berekening van het overstromingsrisico* (Tech. Rep.). Rijkswaterstaat. Retrieved from http://publicaties.minienm.nl/download-bijlage/59478/dww-2006-010-risicocase-dijkring-14.pdf

Minister J. R. H. Maij-Weggen. (1994, February). *Vaststelling van de begroting van de uitgaven en de ontvangsten van hoofdstuk xii (ministerie van verkeer en waterstaat) voor het jaar 1994.* Letter. Retrieved from http://resourcessgd.kb.nl/SGD/19931994/PDF/SGD_19931994_0004825.pdf

Ministerie van Verkeer en Waterstaat. (2006, September). *Stormvloedkering nieuwe waterweg, innovatief sluitstuk deltawerken.* Retrieved from http://park.org/Netherlands/pavilions/techno/svk/hartel/werkingdraagsysteem.html

PIANC Working Group 26. (2006). *Design of movable weirs and storm surge barriers* (Tech. Rep. No. ISBN 2-87223-154-4). PIANC. Retrieved from http://pianc.us/workinggroups/docs_wg/incom-wg26.pdf

Prett, M., & Olson, E. (2010, April). *Big butte feasibility study* (Tech. Rep.). Brown and Caldwell. Retrieved from http://www.oregon.gov/22393D2B-09A5-4EC5-85BA-1F6603C2E88C/FinalDownload/DownloadId-0970DC1CE505F9B7637302AF622F2222/22393D2B-09A5-4EC5-85BA-1F6603C2E88C/owrd/law/docs/GrantApp/GC0028_09Big_Butte_Feasibility_Report.pdf (Prepared for Eagle Point Irrigation District/Medford Water Commission Willow Lake Enhancement Project) prof. drs. ir. J. K. Vrijling, drs. A. Roos, dr. B. J. M. Ale, van der Brand, D., ir. L. de Bruyn, dr. K. G, B. d. M., ... prof. dr. ir. J. F. Agema (2002). *Probability in Civil Engineering* (H. K. T. Kuijper, Ed.) (No. ISBN 90 376 0102 2). TU Delft.

prof. ir. drs. J. K. Vrijling, ir. H. K. T. Kuijper, dr. ir. S. van Baars, ir. K. G. Bezuyen, ir. W. F. Molenaar, van der Hoog, C., ... ing. M. Z. Voorendt (2011). *Manual Hydraulic Structures* (, Ed.) (No. CT3330). TU Delft.

Rienstra, S., & Groot, W. (2012, September). *Advies te hanteren discontovoet bij de Life Cycle Cost analyse.* Note. Retrieved from `http://www.kimnet.nl/sites/kimnet.nl/files/advies-te-hanteren-discontovoet-bij-de-life-cycle-cost-analyse.pdf` (Kennisinstituut voor Mobiliteitsbeleid)

Rijkswaterstaat. (-). *Maeslantkering.* Retrieved from `http://www.rijkswaterstaat.nl/water/veiligheid/bescherming_tegen_het_water/Deltawerken/Maeslantkering/`

Rijkswaterstaat. (2014, June). *Helpdesk water trefwoord 30juni 14.* Retrieved from `www.helpdeskwater.nl/publish/.../helpdesk_water_trefwoord_30juni_14.xls`

Schiereck, G. J. (2012). *Introduction to bed, bank and shore protection* (2nd ed.; H. J. Verhagen, Ed.) (No. ISBN 978-90-6562-306-5). VSSD.

Soy, S. K. (1997). *The case study as a research method.* Retrieved from `https://www.ischool.utexas.edu/~ssoy/usesusers/l391d1b.htm` (Unpublished paper, University of Texas at Austin)

Stichting Deltawerken Online. (2005, February). *Deltawerken online.* Retrieved from `http://www.deltawerken.com/`

Trading Economics. (2014). *Euro area inflation rate.* Retrieved from `http://www.tradingeconomics.com/euro-area/inflation-cpi`

van Breukelen, M. (2013). *Improvement and scale enlargement of the inflatable rubber barrier concept* (A case study applicable to the Bolivar Roads barrier, Texas, USA, Delft University of Technology). Retrieved from `http://repository.tudelft.nl/assets/uuid:3fb26157-ac79-491f-a3bb-94f7fb4d1f61/Final_Master_thesis_M_van_Breukelen_17-12-2013.pdf`

van der Burgh, W. T. J., Lassing, B. L., & van de Paverd, M. (1998, October). *Toetsing op de veiligheid van de Stormvloedkering Nieuwe Waterweg - Europoort en Europoort Hartelkering* (Tech. Rep. No. Helpdesk LTV advies 98045). Rijkswaterstaat, Dienst Weg- en Waterbouwkunde. Retrieved from `http://publicaties.minienm.nl/download-bijlage/44748/toetsing-op-veiligheid-van-de-stormvloedkering-nieuwe-waterweg-europoort-en-europoort-hartelkering.pdf`

van der Laken, S. (1999). *Ontwerp van schuiven van de Oosterscheldekering in vezelversterkte kunststoffen* (Master's thesis, Delft University of Technology). Retrieved from `http://publicaties.minienm.nl/download-bijlage/28603/40957.pdf`

van Grootveld, I. (2014, May). *Inspectierapportage balgstuw Aalsmeer - Inspectie en hersteladvies balgstuw Aalsmeer op basis van rapportage Fairbanks Nijhuis* (Tech. Rep.). Hoogheemraadschap van Rijnland.

van Ledden, M., Lansen, A. J., de Ridder, H. J., & Edge, B. (2012, July). Reconnaissance level study Mississippi storm surge barrier. In P. Lynett (Ed.), *Coastal engineering. conference. 33rd 2012.* Curran Associates, Inc. (Dec 2013).

van Vugt, E. A. (2008). *Protecting New Orleans: Revision of the hurricane protection system in order to prevent Lake Borgne induced flooding during hurricanes* (Master's thesis, Delft University of Technology). Retrieved from `http://repository.tudelft.nl/view/ir/uuid%3A63be2440-afa8-4135-bf96-325c04b3bdf1/`

Welsink, M. W. J. (2013). *Adaptation of the Hollandsche IJssel storm surge barrier* (Master's thesis, Delft University of Technology). Retrieved from `http://repository.tudelft.nl/view/ir/uuid%3A38b16f7d-3350-4e9d-b963-a69febd2714a/`

Woodward, D. G. (1997). Life cycle costing - theory, information acquisition and application. *Pergamon International Journal of Project Management*, *15*(6), 335 - 344.